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TECHNICAL REPORT RH-CR-81-8

MM&T: TESTING OF ELECTRO-OPTIC COMPONENTS

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February 1981

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Aerodyne Research, Inc. has studied the testing of electro-optic components with special emphasis on diamond-turned optics. The primary purpose of that study was to determine where new government initiatives could be most effective in moving this area forward. Besides an ordered list of recommended government actions, this study has resulted in: an extensive survey of experts (the most extensive yet made), the largest annotated bibliography in the field, an improved form of Ronchi testing

giving quantitative results, a general approach to nonconjugate interferometry, a high-accuracy form of multiple-wavelength absolute distance interferometry, and a totally new approach to the generation of test holograms by computer. The recommended fields for government action follow:

Computer Generated Holograms

Holographic testing for deep aspheres has been demonstrated by many people. To date, the technique is severely limited because the number of resolvable elements that can be written by a computer controlled plotter is excessively small. A new technique developed by Aerodyne Research, Inc. can remove these limitations and thus allow holographic lens testing to be used at high accuracy for deep aspheres. Developing this is by far the most important thing the Government can do to aid in the testing of machined optics.

Scatter Monitor

Developing such an instrument would be straightforward and only moderately expensive. Subsequent units would cost less than half the development price.

Nonconjugate Interferometry

For some tasks this is very important. In our judgement this requires a development effort preceding system construction. Thus it requires a multi year effort. Both the geometry and the interferometer were designed in this work.

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EXECUTIVE SUMMARY

Aerodyne Research, Inc. has studied the testing of electro-optic components with special emphasis on diamond-turned optics. The primary purpose of that study was to determine where new government initiatives could be most effective in moving this area forward.

Besides an ordered list of recommended government actions, this study has resulted in

- an extensive survey of experts (the most extensive yet made),
- the largest annotated bibliography in the field,
- an improved form of Ronchi testing giving quantitative results,
- a general approach to nonconjugate interferometry,
- a high-accuracy form of multiple-wavelength absolute distance interferometry, and
- a totally new approach to the generation of test holograms by computer.

The recommended fields for government action follow.

<u>Computer Generated Holograms</u>

Holographic testing for deep aspheres has been demonstrated by many people. To date, the technique is severely limited because the number of resolvable elements that can be written by a computer controlled plotter is excessively small. A new technique developed by Aerodyne Research, Inc. can remove these limitations and thus allow holographic lens testing to be used at high accuracy for deep aspheres. Developing this is by far the most important thing the Government can do to aid in the testing of machined optics.

Scatter Monitor

Developing such an instrument would be straightforward and only moderately expensive. Subsequent units would cost less than half the development price.

Nonconjugate Interferometry

For some tasks this is very important. In our judgement this requires a development effort preceding system construction. Thus it requires a multi year effort. Both the geometry and the interferometer were designed in this work.

1. INTRODUCTION

1.1 Goals

Testing of electro optical components of interest to manufacturers of those components (to assure cost-effective production) and to the government (for specification design, acceptance testing, and in-use evaluation). This program was intended to survey needs in this area and to recommend specific steps the government could take to make the testing more effective.

While the testing methods we describe are broadly applicable, we have placed particular emphasis on the important new field of diamond turned optics.

1.2 Criteria

Test methods were judged by criteria furnished in the statement of work. These were guidelines only, because the criteria came into conflict when applied to some particular cases. The criteria were guidelines rather than constraints. The five criteria were

- surface specification,
- flexibility,
- interpretability,
- simplicity, and
- acceptability.

It is convenient to explain these by five figures, Figs. 1.1 through 1.5. It is abundantly clear that satisfying all of these criteria simultaneously may be very difficult or even impossible. Certainly flexibility and simplicity are often antagonistic. If no present system satisfies the first four criteria, new ones must be designed. But new systems are always slow in gaining acceptability, the fifth criterion. Thus tradeoffs are necessary and desirable.

- DEFICIENCIES MUST BE LOCATED SPATIALLY - THIS EXCLUDES GLOBAL MEASUREMENTS

- DEFICIENCIES MUST BE DESCRIBED FULLY AND QUANTITATIVELY - THIS ALLOWS CORRECTIONS IN SOME CASES

Figure 1.1 Explanation of the criteria of "Surface Specification"

THE FINAL INSPECTION SYSTEM MUST HANDLE
THE FOLLOWING RANGE OF INPUTS:

PROPERTY	VARIABLE
• COMPLEXITY	• SINGLE SURFACE TO MULTI-SURFACE SYSTEM
• INTENDED OPERATING DOMAIN	• VISIBLE TO INFRARED
• OPERATING PRINCIPLE	• REFRACTIVE TO REFLECTIVE
• FINISH	• POLISHED TO DIAMOND TURNED
• FUNCTION	• IMAGING TO NONIMAGING

Figure 1.2 Explanation of the criterion of "Flexibility"

- THE TESTS MUST BE IMMEDIATELY INTERPRETABLE TO TECHNICIANS IN "INTUITIVE", SEMI-QUANTITATIVE FORM
- THE TESTS MUST YIELD QUANTITATIVE MEASUREMENTS OF SUFFICIENT ACCURACY TO SERVE ALL REASONABLE SPEC-IFICATION NEEDS
- THE SPECIFICATIONS MUST BE EASILY ARRIVED AT FROM SPECIFICATIONS GIVEN IN SOME OTHER WAY

Figure 1.3 Explanation of the criterion of "Interpretability"

- THE SYSTEM MUST BE OPERABLE IN

    LABORATORY,

    OPTICAL SHOP, AND

    FIELD

  ENVIRONMENTS

- THE SYSTEM SHOULD BE SIMPLE ENOUGH TO BE INEXPENSIVE AND EASILY USED

Figure 1.4 Explanation of the criterion of "Simplicity"

THE SYSTEM SHOULD WIN WIDESPREAD

ACCEPTANCE IN THE OPTICS COMMUNITY

Figure 1.5 Explanation of the criterion of "Acceptability"

1.3 Approach

During this work, our effort was divided into two major parts - survey and analysis. The survey was in turn, divided into two parts: survey of experts and collection of bibliography. Likewise, the analysis was divided into two parts - figure testing and surface condition testing. This report covers the survey, the analysis, and our recommendations based on them.

2. SURVEY

2.1 Poll Of Experts

2.1.1 Introduction

The poll of experts proved very enlightening. In order to make its results more widely available, we have prepared a paper on it.

2.1.2 Formal Paper

Appendix A is a paper entitled "Optical Testing Methods - A Survey Of Experts" which we have prepared for publication.

2.1.3 "Dear John" Letters

Some of the respondents to the poll wrote notes to the senior author of this report (John Caulfield). These "Dear John" letters are useful and interesting. The full set (with identity of the expert deleted) is attached as Appendix B.

2.2 Bibliography

Using the standard computer and library search procedures, we compiled an extensive bibliography on testing methods. We have transferred that bibli - graphy to a page composer, so we can insert new material wherever it is appropriate without difficulty. Although this bibliography is undoubtedly incomplete and already out of date, it appears to be both unique and valuable. Aerodyne Research, Inc. will make the complete print out available to anyone at our cost plus a nominal fee. Our hope is to keep this bibliography updated. A full print out has been delivered to the sponsor and a few sample pages are shown in Appendix C. The categories covered are given in the following list:

CONTENTS OF TESTING METHODS BIBLIOGRAPHY

1. Newton, Fizeau and Haidinger Interferometers

(a) Newton Interferometer

(b) Fizeau Interferometer

(c) Haidinger Fringes

2. Twyman-Green and Williams Interferometers

3. Common Path Interferometer

(a) Burch Interferometer

(b) Fresnel Zone Plate Interferometer

(c) Birefringent and Polarization Interferometers

(d) Koster's Prism Interferometer

4. Lateral Shearing Interferometer

(a) General

(b) Koster's Prism Interferometer

(c) Murty Interferometer

(d) Birefringent and Polarization Interferometers

5. Other Shearing Interferometers

(a) Radial Shearing Interferometers

(b) Rotational and Inverting Interferometers

6. Multiple Reflection Interferometers

(a) Single Source Interferometers

(b) Multiple Source Interferometers

(c) Fringes of Equal Chromatic Order

7. Mutliple Pass Interferometers

8. Foucault and Wire Tests
   (a) Foucault Knife-Edge Tests
   (b) Wire and Double-Wire Tests
   (c) Ritchey - Common Test For Flat Mirrors
   (d) Zernike Phase - Contrast Test

9. Ronchi and Lower Tests
   (a) Ronchi Test
   (b) Lower Test

10. Hartmann and Michelson Tests

11. Star Test

12. Holographic and Moire Techniques
   (a) Interferometers Using Real Holograms
   (b) Interferometers Using Synthetic Holograms
   (c) Two-Wavelength Interferometers
   (d) Use Of Moire Fringes

13. Null Tests Using Compensators
   (a) Dall-Kirkham and Offner Compensators
   (b) Other Null Compensators

14. Measurement of Angles and Alignment
15. Measurement of Radii of Curvature and Focal Lengths
16. Roughness Measurements
17. Testing of Glass Homogeneity
18. Miscellaneous
19. Review Papers
20. Books

21. LUPI
22. Machined Optics
23. Aspheres
24. Image Evaluation
25. Cylindrical, Lenses, Axicons, etc.
26. Computer Data Reduction

3. ANALYSIS

3.1 Surface Figure Testing

3.1.1 Surface Shape Considerations

3.1.1.1 Introduction

The surface shape profoundly affects the choice of test method. With diamond-turned optics the surface shapes are often aspheric and sometimes non focussing. These shapes offer unique problems.

3.1.1.2 Spherical surfaces

Because spherical (including planar) wavefronts are easy to create, the interferometric comparison of a spherical reference wavefront with a wavefront derived by a spherical surface is straightforward. A variety of commercial organizations sell excellent hardware and software for this purpose. This is obviously not a place where new government initiatives will help greatly.

3.1.1.3 Aspheric surfaces

Diamond turned ellipsoids, parabolas, and other focussing aspheres are sometimes hard to test with conventional, spherical interferometers. The problem can be stated in many ways. If we regard the fringes as contours of phase difference from a reference sphere, we can see that some parts of some aspheres will produce fringes so crowded together that useful analysis is precluded.

The way to restore equal spaced fringes is to insert a special, compensating lens called a "null lens". Null lenses themselves may be hard to design, construct, and test.

Fortunately there is a very general technique which can produce accurate null lenses quickly and easily. That technique (see appendix) uses computer generated hologram null lenses. These work very well. No further research is needed. The only problem is that the skills, computer codes, and equipment to design, build, and test these are not readily available. Making those skills and facilities available for fast-response, moderate-cost, certified-accurate null lens design and generation is one way the government can assist optical testing in a substantial way. A plan to do this is given in Section 4.2.

3.1.1.4 Non focussing surfaces

For nonfocussing surfaces, e.g. axicons, classical interferometry is often impossible. In some cases additional optics (themselves hard to construct and test) can be used to make a "system" which can be tested by classical interferometry. More often, classical interferometric testing is simply precluded. Our analysis of this problem and our proposed solution follow.

Interferometry is a widely-used technique for metrology of spherical and near spherical surfaces. A typical arrangement is shown in Fig. 3.1. The light in the "object arm" is converged to the center of the test sphere. The test sphere then retroreflects the incident light back through the beam splitter to an image plane where it interferes with the reference beam to form an interference pattern which must be interpreted as a contour map of the object surface relative to the reference surface. The use of this retroreflecting geometry is an example of "conjugate interferometry". The variety of conjugate geometries is very large. Unfortunately conjugate geometries are not always possible. Some surfaces, e.g. non-focusing ones, are not directly usable because they can not be caused to retroreflect. Often they can be put into systems which are focussing, so the net system can be tested. Other surfaces can not be made to retroreflect without the construction of other bizarre, untestable surfaces.

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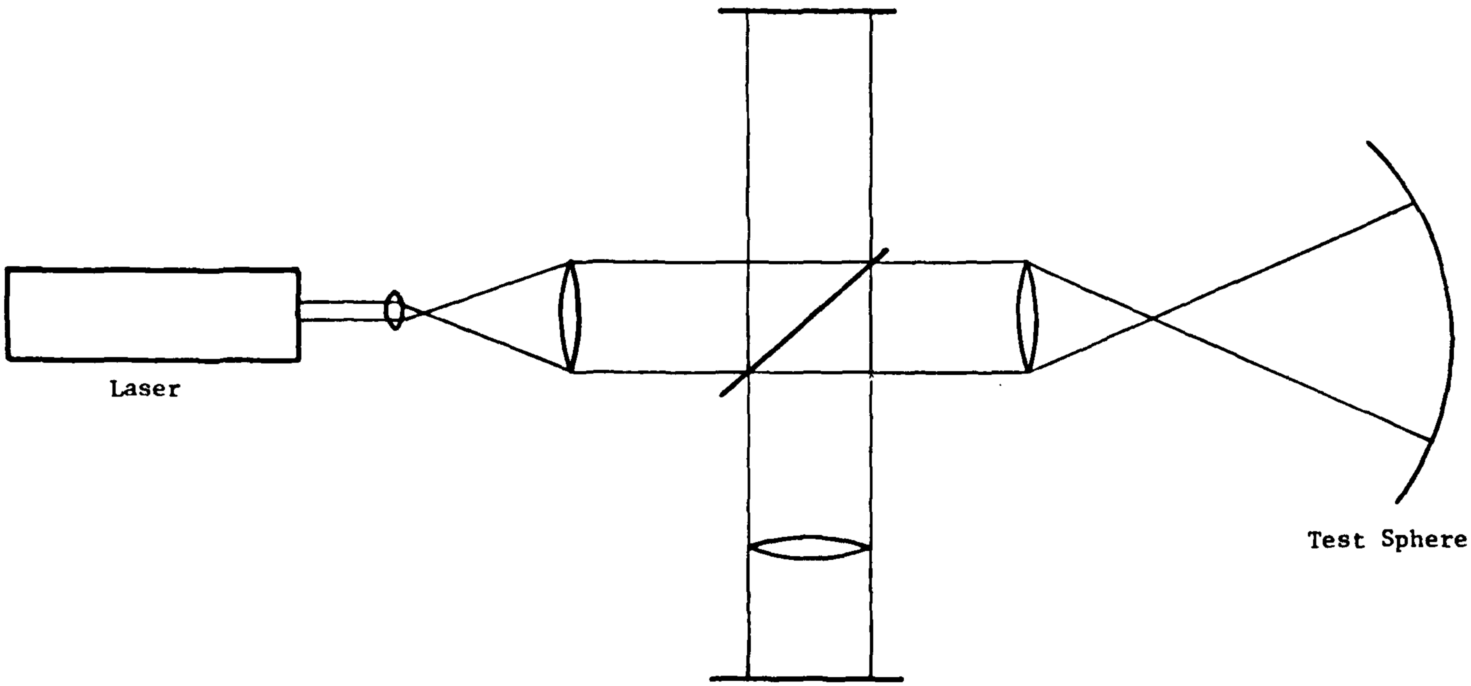

Figure 3.1 Simple conjugate interferometer arrangement

Another case in which conjugate testing is impossible is that in which the desired alignment is unattainable, unknowable, or unguaranteeable. These special but common cases indicate a widely-felt need for some type of non-conjugate interferometry. It is this problem we address.

The two basic ideas are: (1) do the measurements one object point at a time and (2) use the cat's eye principle to convert normally-nonconjugate specular scatter into conjugate scatter. There are numerous conceivable ways to do this. We will show two very different approaches.

We imagine that we have an unknown surface to evaluate interferometrically. Our approach will be to describe it point-by-point in spherical coordinates r, θ, and ϕ with $r = 0$ at a convenient place on our instruments. We set the angular coordinates to some positions θ_o, ϕ_o and measure $r_o = r(\theta_o, \phi_o)$.

Conceptually, we can change θ and ϕ with a mirror. Figure 3.2(a) shows the mirror at $r = 0$ in retroreflection position. Figure 3.2(b) shows the mirror rotated to give θ_o, ϕ_o which, in this case, directs the beam to a corner cube at a range r_o. Obviously the difference in optical path differences (OPD's) in the two cases is simply $2r_o$. Several interferometric means for measuring r_o are available. In this way, if the object were comprised of corner cubes, we could map out the surface.

Since real objects are not made of corner cubes, we want to capture the light they do scatter and bring it back to the detector parallel to and overlapping the light from the reference arm of the interferometer. Furthermore, we want to keep the OPD at $2r_o$ regardless at what angle(s) the light is scattered. A well-corrected and focussed lens will do just that as shown in Fig. 3.3. Because the OPD is angle-independent we can read r_o at all θ_o, ϕ_o such that the surface does not scatter out of the angular collection region of the lens. Of course, in the detector plane, nonconjugate illumination shares the return beams from the two arms apart as suggested in Fig. 3.4. We can either measure over the full reference beam pattern and accept a lowered depth of modulation or measure only over a small local area and accept some loss of power.

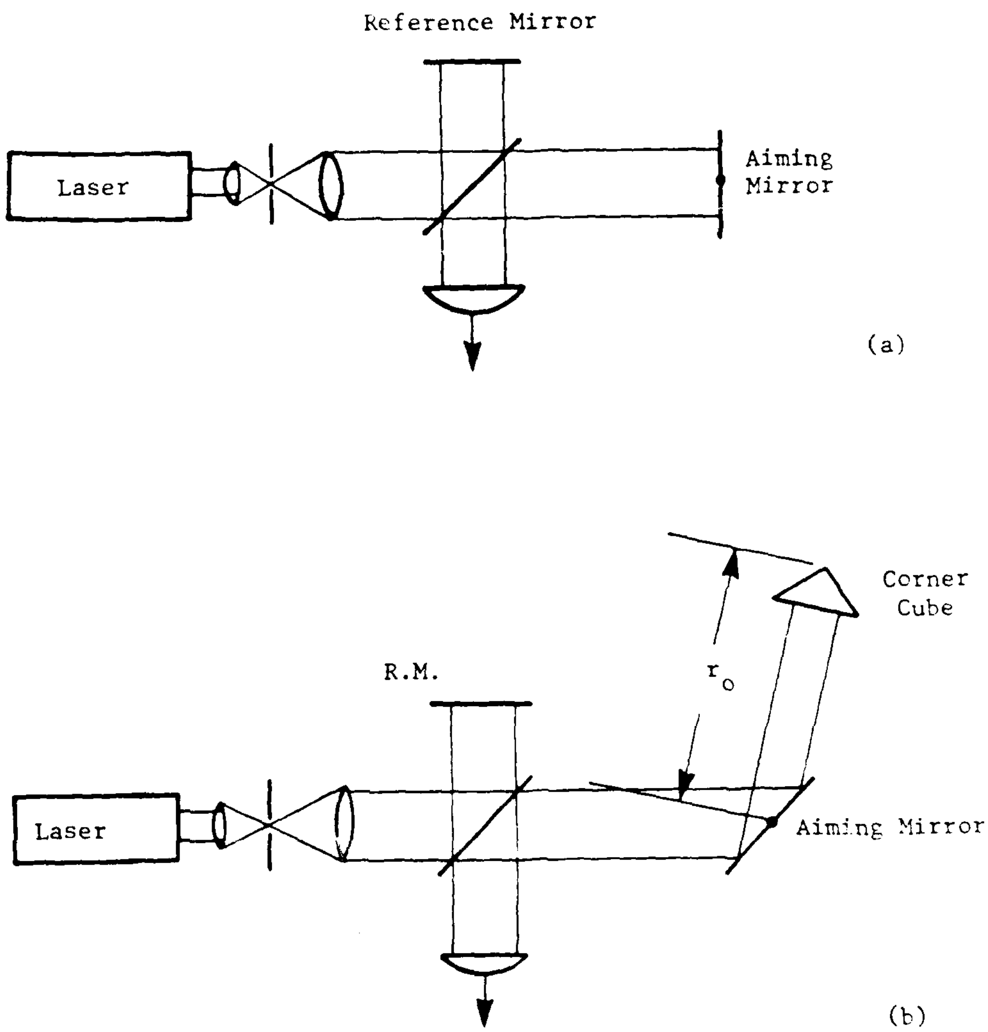

Figure 3.2 Using an aiming mirror, we can measure the range of points from the center of the mirror by subtracting the optical path differences for the two cases shown here

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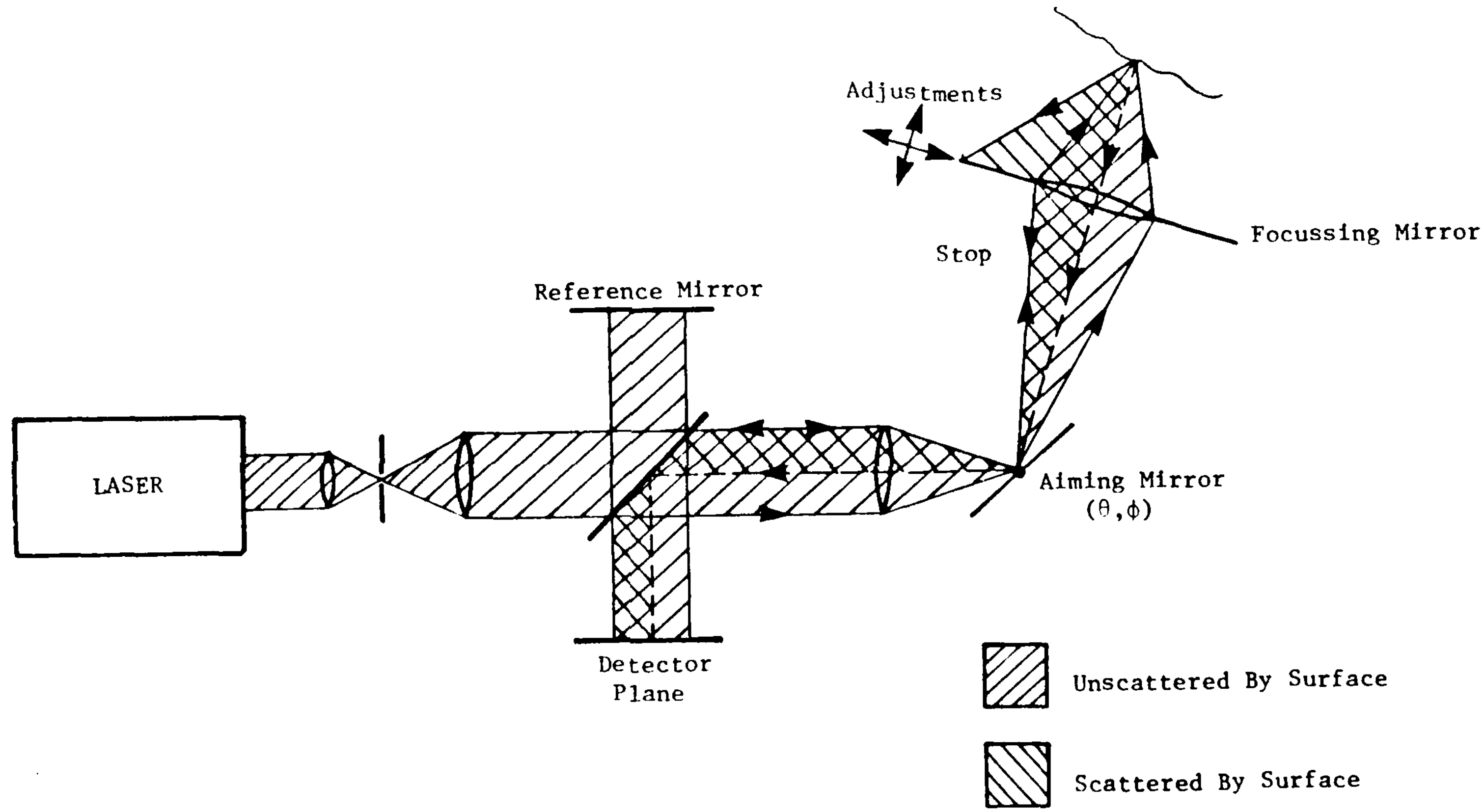


Figure 3.3 Nonconjugate Interferometer

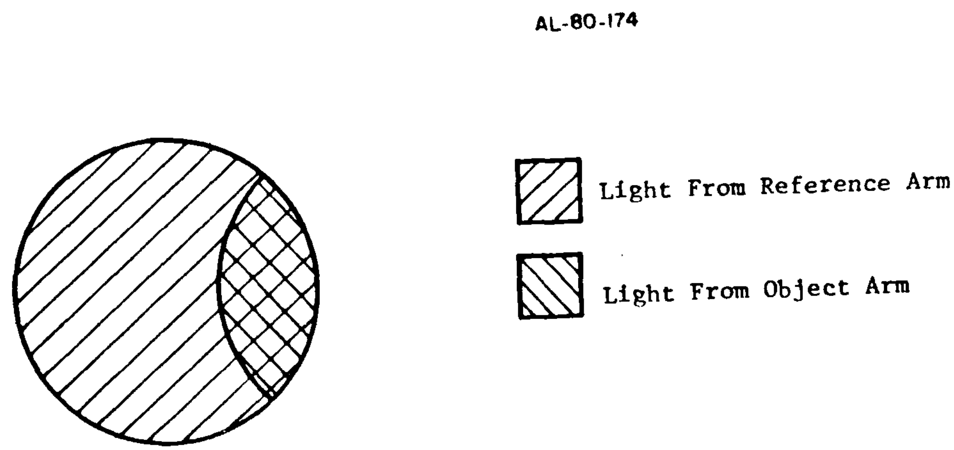


Figure 3.4 Detector plane for non conjugate case

It is also clear that we can measure not only $r(\theta_o,\phi_o)$ but also $dr/d\theta$ and $dr/d\phi$ at the same θ_o,ϕ_o. This extra information is useful in describing the surface and can be obtained with little extra effort.

We are left with the problem of describing the surface in a more ordinary and useful format than in spherical coordinates from a nonconjugate point whose position may not be known precisely a priori. While this is strictly a mathematics problem it may be quite non trivial. It seems logical to use our a priori knowledge of the surface shape and location of the center of the spherical coordinates to obtain best fits to the six solid-body kinematic parameters (three translation and three rotation) of the surface. We could then posit those parameters and describe all differences between observations and a priori prediction for those parameters as perturbations in the surface shape. Such a description is mathematically valid but not mathematically unique in that a perturbation of the parameters would change our description of the shape perturbations.

Like most solutions to hard problems, this one is simple in retrospect. The only general way we know of causing retroreflection from a point on an arbitrary surface is to focus light onto that point. Such "cat's eye" retroreflection systems are well known. By doing this we change a nonconjugate system into a conjugate one. In one sense, then, we have not solved the problem. We are still doing conjugate interferometry. In the same sense, however, there never was a problem to solve. Interferometry requires retroreflection (conjugation). We have simply shown that we can retroreflect off points on a very general, unknown surface with an adaptive, one-point-at-a-time optical system. This is, of course, a far more general approach than normal conjugate interferometry which makes use of our a priori knowledge of the test object to construct a special-purpose retroreflector.

To scan, we use a combination of mirror scanning for large angle scans and lens translation for local angle scans. The optical axis can be tracked easily as it lies along the line from the $r = 0$ point to the lens center. Focus can be adjusted by lens motion along the optical axis.

The total angular scan by lens motion is limited by the angle of the beam focussed on the turning mirror. To obtain a larger scan we must "bootstrap" by turning the mirror, adjusting the focussing/collecting lens, and piecing the overlapped fields of view together by computer. While possible, this is difficult. Therefore we seek a simpler approach.

The simplest scanner we have devised is an x-y stage which carries the test object. The x-y location can be monitored and controlled interferometrically to a small fraction of a wavelength.[3-1] Motion can be quite fast as well.[3-1] Focus can be maintained by a focus servomechanism moving the lens along the optical axis and working on the peak in return signal as the best focus is traversed.[3-2]

The two primary geometrical restrictions stem from (1) the necessity of having some of the specular light collected by the focussing/collecting lens and (2) the need to restrict the depth variation over the focussed spot to less than the required depth measurement accuracy. The latter requirement is far more restrictive than the former. Consider an inclined plane object and a focussing/collecting lens of focal number N. The focussed spot has a diameter of about $N\lambda$, where λ is wavelength. If we want to measure to λ/M accuracy, the inclination of the plane (relative to a plane normal to the optical axis) must not exceed

$$\theta_o = \tan^{-1}(1/MN). \tag{3-1}$$

With a N = 1 lens we can achieve $\lambda/10$ accuracy only for inclinations less than about 0.1. To give another indication of this restriction, let us find what focal number, N_L, spherical lens would be limited to λ/M at its edge. Regarding the lens as locally flat, we can analyze using Fig. 3.5. We have

$$N_L = f/A \tag{3-2}$$

and

$$\tan 2\theta_o = 1/2N_L . \tag{3-3}$$

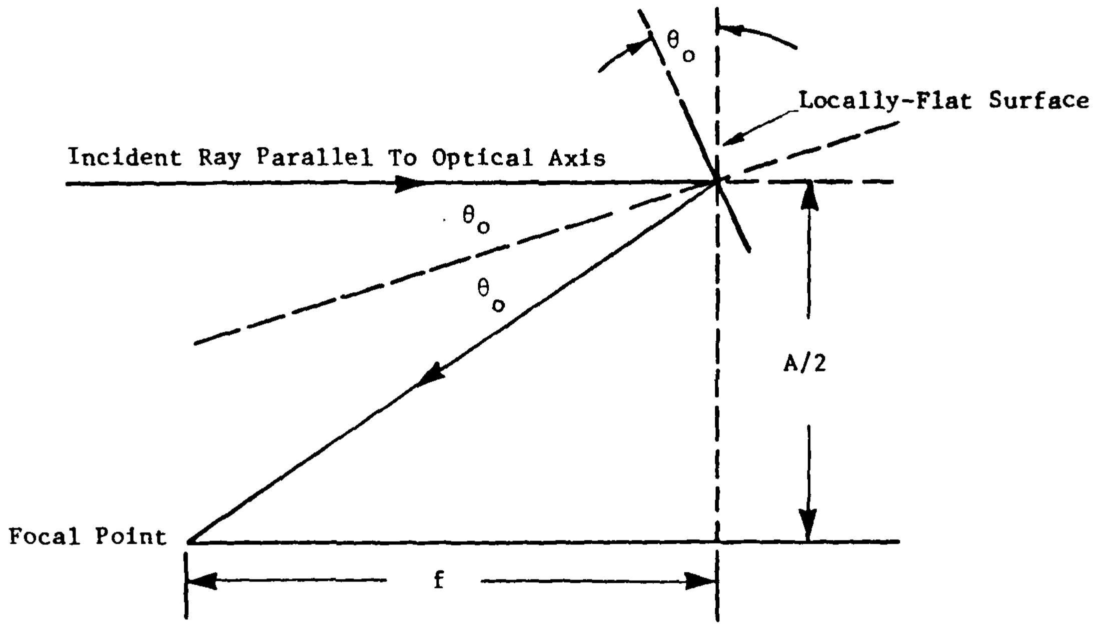


Figure 3.5 Figure useful in relating focal to achievable accuracy

Thus

$$\tan\left\{\left[2\tan^{-1}(1/MN)\right]\right\} = 1/2N_L. \tag{3-4}$$

For $\theta_o \ll 1$,

$$\tan^{-1}(1/MN) \simeq 1/MN \tag{3-5}$$

and

$$\tan\{2/MN\} \simeq 2/MN. \tag{3-6}$$

Thus

$$4N_L \simeq MN. \tag{3-7}$$

If $N = 1$ and $M = 10$, we have

$$N_L \simeq 2.5. \tag{3-8}$$

Nonconjugate interferometry can be performed in several ways. We have discussed two approaches. Both approaches use external controls to position the interrogation point laterally and bring it to focus. Both approaches use absolute distance interferometry[3-3] to measure the range to the object point. Neither approach works for arbitrarily shaped surfaces, but both offer a substantial increase in the number of situations amenable to interferometry. For example, by object scanning we could examine a large focal length mirror from a convenient distance (much less than the focal length). Thus nonconjugate interferometry fulfills our need for greater flexibility with undiminished accuracy.

In our judgement, nonconjugate interferometry is a highly-important field for further government research. Section 4.4 will suggest some research directions.

3.1.2 Surface Roughness Considerations

Because the diamond-turned surfaces are scarred by the tool, they scatter light. In some circumstances that scatter is so severe as to preclude normal, visible-light interferometry. More commonly, visible light interferometry "works" but the fringes are immensely complicated because they bear information on this surface detail as well as information on the surface figure.

Fortunately there are several available approaches to solving this problem. First, we can use infrared, e.g. 10.6 μm, interferometry. This often suffices to produce fringes characteristic of the figure but not fringes related to the surface detail. Again commercial systems are available. Second, the software can "smooth out" these fringes. Third, there are laboratory methods which can be adapted to commercial interferometry. One such method is double exposure interferometry at two visible wavelengths, λ_1 and λ_2. The moire pattern between the interferograms is the interferogram one would achieve with a wavelength

$$\Lambda = \lambda_1\lambda_2/|\lambda_1 - \lambda_2| \quad . \tag{3-9}$$

3.1.3 Accuracy Considerations

3.1.3.1 Basic analysis

Commercial interferometers can, under proper conditions, achieve $\lambda/100$ accuracy in the visible. As diamond turned optics invades the ultra violet, even greater accuracy may be needed.

We have devised an interferometer based on old principles (multiple wavelength interferometry) and new technology (tunable lasers and phase sensitive detection) which appears to offer greater accuracy as well as to offer the absolute distance measurement required for our nonconjugate interferometry scheme.

The problem we address is the absolute measurement to ultra high accuracy of the distance between a fixed point (part of the measurement apparatus) and a remote retroreflecting point. Ultra high accuracy requires interferometry, but most interferometers measure distances to a modulo of the wavelength and are thus not absolute measurements. Our method can attain absolute accuracies of a small fraction of a wavelength over distances up to millions of wave-lengths, corresponding to accuracies in the range of one part in 10^9.

To determine an optical path distance (OPD) absolutely, we need the fringe order number (the integer giving the whole number of wavelengths in the path), the "excess fraction" (the additional fraction of a wavelength), and the wavelength. We use tunable lasers to obtain a "perfect" path match at two wavelengths, λ_1 and λ_2. From the easily-measured wavelength difference, we can determine the fringe order number exactly if we know the OPD to within $\lambda_1\lambda_2/|\lambda_1-\lambda_2|$ by some other means. We utilize techniques borrowed from ultra-high resolution tunable laser spectroscopy[3-4] to obtain the path matches with the required accuracy. Of course, knowing the fringe order number and the wavelength, we can calculate the OPD directly.

Our primary intent in this work was to do point-by-point interferometry of complex surfaces and in this way achieve a type of nonconjugate interferometry.

There are several other applications. In normal conjugate interferometry a one-part-in-10^9 accuracy would give extreme accuracy. As we shall see, our method inherently uses only one point at a time. Thus the extreme accuracy is achieved at a price of serial (as opposed to the usual parallel) interrogation of image points.

An ideal application is the stereometric determination of the location of retroreflectors deliberately attached to a remote object. Alignment of multielement large mirrors in space is an example of a problem readily amenable to this approach.

As might be expected, our solution is not entirely new. Indeed, it is based on nineteenth century science. What we have done is to improve and refine the old techniques taking full advantage of 1980 technology.

So far as we have been able to determine, the development of a means of measuring the distance between two points interferometrically without marching from the first point to the second, was first developed by Benoit in 1898, using several spectral lines with the method of excess fractions.[3-5] The principle involves measuring the path difference in two legs of an interferometer by solving the set of simultaneous equations $L = n(\lambda/2) + \varepsilon$ for the "phase" ε. By choosing different values of λ, a system of equations is possible which specifies L, knowing ε, if n is taken to be an integer. This technique was applied to measure Optical Path Differences (OPD's) of as large as 10 cm to obtain accuracies within a fraction of a wavelength of light.

The technique of Benoit was extended to measuring much longer distances by the use of CO_2 laser.[3-6,3-7] While the principles were the same, the use of a CO_2 laser allowed for a much more stable light source, and the high powers available allowed for the longer distance measurements. The limit in accuracy, however, still depended on the accuracy in determining the phases of different colors of light. Moreover, the absolute distance is determined by solving a set of equations involving the use of different precisely tuned wavelengths. Our system involves the use of only one absolute standard, and tunable light sources which are compared to this absolute standard.

Let L be the OPD between two legs of an interferometer. If light having the wavelength λ_1 is used in the interferometer, and the phase of the interference when the two legs are combined is given by ϕ_1, then

$$L = n_1 \lambda_1 + \phi_1 \lambda_1 / 2\pi \quad , \qquad (3.10)$$

where n is often referred to as the fringe order number. If more than one wavelength of light is used, we have a set of N simultaneous equations

$$L = \left(n_1 + \frac{\phi_1}{2\pi}\right)\lambda_1 = \left(n_2 + \frac{\phi_2}{2\pi}\right)\lambda_2 = \ldots = \left(n_N + \frac{\phi_N}{2\pi}\right)\lambda_N \tag{3-11}$$

We can insure that the partial phase, or excess fraction, ¢, is zero or π by choosing the proper wavelength λ_i.

By solving the set of simultaneous equations (Eq. (3-11)) in L, we have N equations and N + 1 unknowns. An additional constraint is that n_i is an integer. Thus, if we choose two wavelengths λ_1 and λ_2 we obtain the equation:

$$L = n_1\lambda_1 = n_2\lambda_2 = \left(n_2 - n_1\right)\left(\frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_1}\right) . \tag{3-12}$$

Even when L is a long path such that n_1 and n_2 are large numbers, if λ_1 and λ_2 are sufficiently close, the integer $(n_1 - n_2)$ can be counted. We define a new synthetic wavelength;

$$\Lambda = \frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2} . \tag{3-13}$$

We now have

$$L = \left(n_2 - n_1\right)\Lambda . \tag{3-14}$$

If we determine $n_1 - n_2$, and measure Λ, we know L.

Note that it is not important to know the absolute fringe order numbers for λ_1 and λ_2, but only the difference in orders between λ_1 and λ_2. In order to obtain the maximum accuracy, however, this integer difference must be known to an accuracy where either n_1 or n_2 can be calculated. An expression for n_1 in terms of measurable quantities is

$$n_1 = \left(n_2 - n_1\right)\left(\frac{\lambda_2}{\lambda_1 - \lambda_2}\right) = \frac{L}{\lambda_1} \quad . \tag{3-15}$$

From Eq. (3-13) we see that the wavelength Λ has been synthesized by using two wavelengths λ_1 and λ_2. It is much easier, however, to measure frequency than wavelength, particularly for small wavelength differences $\lambda_1 - \lambda_2$. If we add the intensities λ_1 and λ_2 on a square law detector, we see the beat frequency

$$f = \frac{c}{\lambda_2} - \frac{c}{\lambda_1} = c\left(\frac{\lambda_1 - \lambda_2}{\lambda_1\lambda_2}\right) \quad . \tag{3-16}$$

This beat frequency can be substituted into Eq. (3-12) to give the measurement of length:

$$L = \frac{(n_2 - n_1)c}{f} \quad . \tag{3-17}$$

The measurement of the distance L is thus based on knowing the integral order $(n_1 - n_2)$ and measuring very accurately the beat frequency between two lasers which are wavelength tuned to the intensity maxima of their interference.

Note that the shortest OPD which satisfied Eq.(3-17) is given by

$$L_{MIN} = c/f \quad . \tag{3-18}$$

Thus, for a frequency f in the range of 1 GHz, $L \cong 0.3$ m, 0.6 m, ..., etc., and the order $(n_1 - n_2)$ can be determined by visual inspection or from any prior placement accuracy.

The principle of operation for measuring distance is thus to wavelength tune two lasers simultaneously to the same OPD of an interferometer, such that they both produce intensity maximums, then measuring the beat frequency between the two lasers. To do this, there are several frequency and coherence constraints which are now discussed.

A schematic diagram of a representative system is shown in Fig. 3.6. The key to the system is that two lasers are locked to the same interferometer such that the OPD provides intensity maxima or minima to both lasers simultaneously. The wavelength of each laser is controlled by this OPD. The two lasers operate alternately. Each laser is tuned so that its wavelength corresponds to an intensity maximum or minimum of the interference pattern. Even though the lasers are tuned alternately, they effectively time share in the use of the interferometer.

The system tunes each wavelength so that the OPD is either an integral number of wavelengths or an integral plus one-half number of wavelengths. The two wavelengths must span the maximum tuning range of the laser to obtain maximum accuracy. To know precisely when we are on a maximum $(L = n\lambda)$ or a minimum $\left[L = (n + 1/2)\lambda\right]$ of the interference pattern, we tune the OPD (via the reference leg) off the extremum to work on the most sensitive part of the intensity vs. OPD curve. Dithering the OPD about its mean value by at least $\lambda/8$ produces a time varying signal. Using a phase detection system we can tune the laser to achieve a symmetric pattern.

The phase detection system works as follows: The intensity of the interference corresponding to OPD + $\lambda/8$ is compared to the intensity at OPD - $\lambda/8$. The difference in intensity, given as an error voltage, is amplified and used to tune the laser cavity. When the intensity difference is zero, the laser cavity stops tuning.

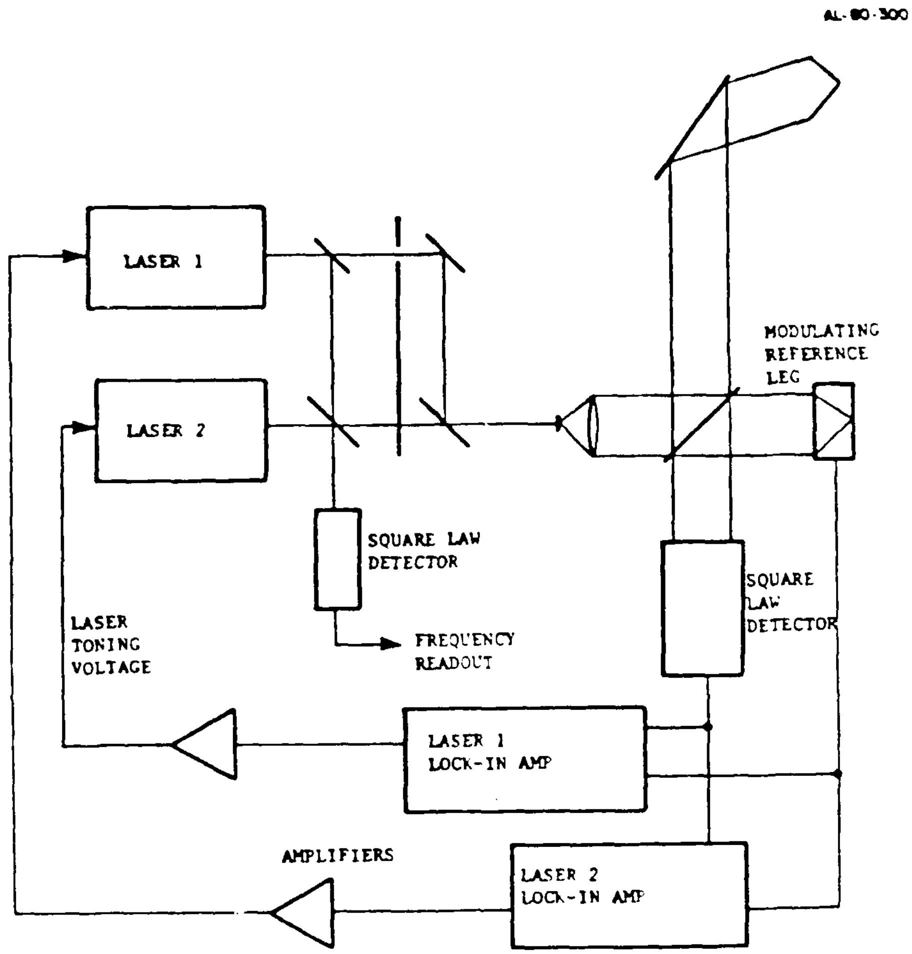


Figure 3.6 Schematic diagram of variable wavelength absolute distance interferometer

The technique described here is applied to two lasers almost simultaneously over the same path. The wavelengths of the two lasers should be either identical or shifted by a precise amount determined by Eq. (3-17). Now if the frequency fluctuations in each laser is smaller than the frequency difference, the frequency difference can be measured to the accuracy of the fluctuations. The beat frequency between the two lasers is measured by splitting off a portion of each laser beam and beating the two beams on the face of a second square law detector. The signal from this detector is fed to a frequency counter, which measures the OPD, L, through Eq. (3-17).

The maximum achievable accuracy of this measurement technique is governed by two parameters; how well one knows the wavelength of the laser light, and how accurately one can measure the phase angle of the interference pattern. From Eq. (3-14), it can be seen that the principal requirement is to determine the modulus n_1 to within a single integer. Since the difference $(n_2 - n_1)$ is known, the precision in determining n_1 from Eqs. (3-15) and (3-16) is

$$\delta n_1 = \frac{c(n_2 - n_1)}{\lambda_1 f^2} \delta f + \frac{c(n_2 - n_1)}{\lambda_1^2 f} \delta\lambda_1 \quad . \tag{3-19}$$

The wavelength accuracy in this system depends on how well we can tune the laser so that the interferometer provides an intensity maximum. The ability to tune to an intensity maximum, on the other hand, depends on how well we can measure small changes in intensity and relate this to small changes in phase. If we modulate the phase around an intensity maximum by dithering the OPD so that the change in intensity with change in OPD is maximum, we obtain the maximum sensitivity. This is given by

$$\delta\phi = \frac{\delta\lambda}{\lambda} = \frac{1}{2\pi} \frac{I}{I_o} , \tag{3-20}$$

where I is the measured intensity and I_o the average intensity of the interference pattern.

Since small differences in intensity are compared at the points of maximum sensitivity, and these differences can be amplified to arbitrary power levels, the limiting sensitivity to phase is given by the shot noise limit of the photodetector. We assume, here, that the modulating frequency of the reference leg is more rapid than intensity fluctuations in the laser.

It may not always be possible to obtain the desired distance modulus n by beating wavelengths λ_1 and λ_2 whose frequencies are separated by a few MHz. As seen from Eq. (3-19), the error δn can be reduced by merely increasing frequency, f. From Eq. (3-20), we see that large wavelength separations do not increase the error in setting the wavelength λ.

From Eq. (3-18), we see that the frequency f can be written as

$$f = (n_2 - n_1) f_o \quad \text{where } f_o = c/L \quad . \tag{3-21}$$

Thus, for the same OPD, the frequency f can be increased by going to larger values of $(n_2 - n_1)$. Thus, for a given accuracy in $\delta\lambda/\lambda$, maximum accuracy in n_1 is obtained by maximizing f, providing that $n_2 - n_1$ can still be determined. To determine $n_2 - n_1$, the synthetic wavelength Λ (see Eq. (3-14)) can be substituted into Eq. (3-19) for λ_1 and $\delta(n_2 - n_1)$ for δn_1. Thus, by using an intermediate step, the accuracy of setting the wavelength is relaxed by the square root.

The coherence length of each laser must be long enough so that the intensity variation at the interference pattern is a function of phase error. This is automatically satisfied by the natural linewidth of the laser line.

The measurement error in frequency depends on how well one can measure a frequency difference. Since the beat frequency is in the radio frequency range, very accurate electronics are available. The requirement for accuracy is thus based on the uncertainty principle, and the frequency accuracy is based on the measurement time.

A new method has been proposed for making absolute distance measurements based on changing the wavelength of the light source rather than the more conventional measurement of phase from a light source of a fixed wavelength. With the advent of accurate electronic counters, the difference frequency between two light sources can be measured to great precision. Using modern closed loop frequency locking techniques, the wavelength of a laser can be stabilized to the OPD of the interferometer to the shot noise limit of the detector. By operating at the maximum slope of the intensity signal in the interferometer, this limit is applied always to the smallest variation in phase for a given intensity.

While the system discussed above does not specify the actual laser source, we note that such lock-in techniques have been used in stabilizing HeNe lasers using the hyperfine lines of I_2.[(3-8)] The shot noise limited stabilizing has been demonstrated in these systems.

It has been demonstrated, in using this technique to lock the HeNe laser line to the hyperfine line of I_2, that the sensitivity to the locking is shot noise limited. The shot noise limit for using a 1 mw HeNe laser beam in our system would be 1 part in 10^7. The required accuracy, on the other hand would be 1 part in 10^6 to achieve an unambiguous fringe order number.

If infrared lasers are used with this technique, the frequency lock-in accuracy is relaxed. If two tunable diode lasers are used simultaneously, for instance, the frequency separation of 0.2 cm^{-1}, corresponding to 6 GHz could easily be achieved. At 5 μm, an accuracy of only 1 part in 10^4 would be required to obtain the order of interference, n.

3.1.4 Convenience Considerations

While commercial interferometers meet the normal accuracy needs and multispectral interferometers can give even better accuracy, these systems are complex, expensive, and hard to use. For simplicity, the Ronchi test is known to be excellent. It uses small, inexpensive hardware.

White light is adequate. Results are easy to analyze intuitively and qualitatively. The problem, almost universally believed, is that quantitative interpretation is precluded by the interference effects commonly seen in "Ronchigrams". We have been able to improve Ronchi analysis in a very simple way. Our consultants, Rochelle Prescott and James Wyant, have agreed that the improvement allows quantitative accuracy equal to that of any other system.

From both surveys (see Section 2), we learned that the Ronchi test was the simplest of the test methods and the favorite of optical technicians. Ronchi tests have been universally characterized as "nonquantitative", because they produce fringes which are very hard to interpret (especially with high frequency gratings). Aerodyne with its consultant Rochelle Prescott, has analyzed Ronchi rulings and found a simple variant which gives clean, sharp fringes even with broadband, extended (parallel to the ruling lines) sources. As these fringes are sharp, we are able to achieve quantitative analysis of great accuracy. Our other consultant, Professor James Wyant, who has often labelled the Ronchi test as nonquantitative, has analyzed our results and is in full agreement that our modified Ronchi test is fully quantitative. His sole reservation is that the Ronchi test measures ray directions not surface slopes. As some users choose to specify surfaces by ray direction and translation to surface slope information is straightforward, we do not view that reservation as extremely serious.

The key concept is that the square profile Ronchi ruling should be replaced with a sinusoidal ruling. An experimental test of various rulings was made using an arc lamp source. Figures 3.7 through 3.13 show the image of the test object and, to one side, the image of a point source. The point source image has only a central spot (0 order) and two side spots (+1 and -1) order) for a sine wave grating. Other gratings produce higher order spots as well. Note the improvement in line definition and the absence of light outside the sharp image of the test object for a sinusoidal ruling.

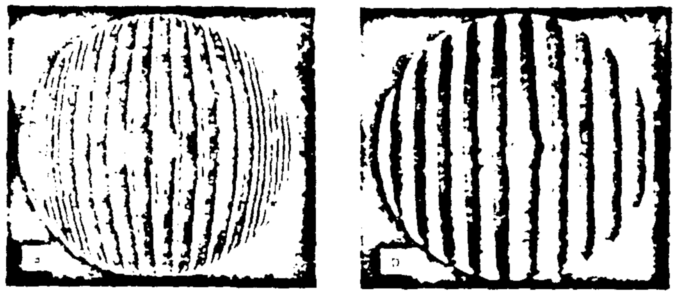


Figure 3.7 Ronchi images representative of typical "best" results of prior work. This represents normal and null tests of a asphere.

From Optical Shop Testing, Daniel Malacara, Ed. John Wiley, New York, 1978, Page 297)

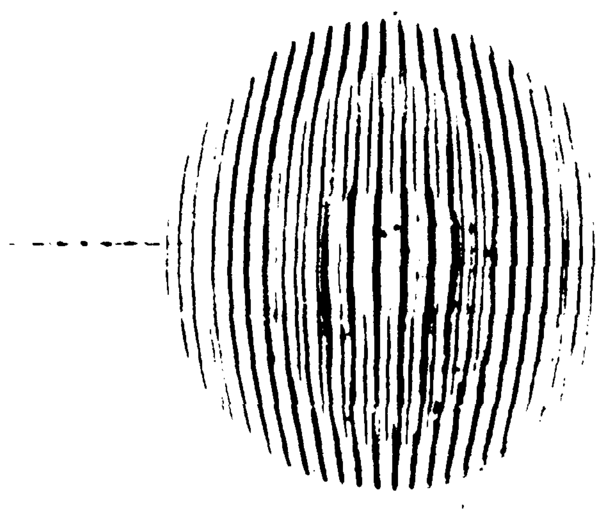


Figure 3.8 In white light the Ronchi images are even worse as shown here, along with the white light point spread function of the Ronchi ruling

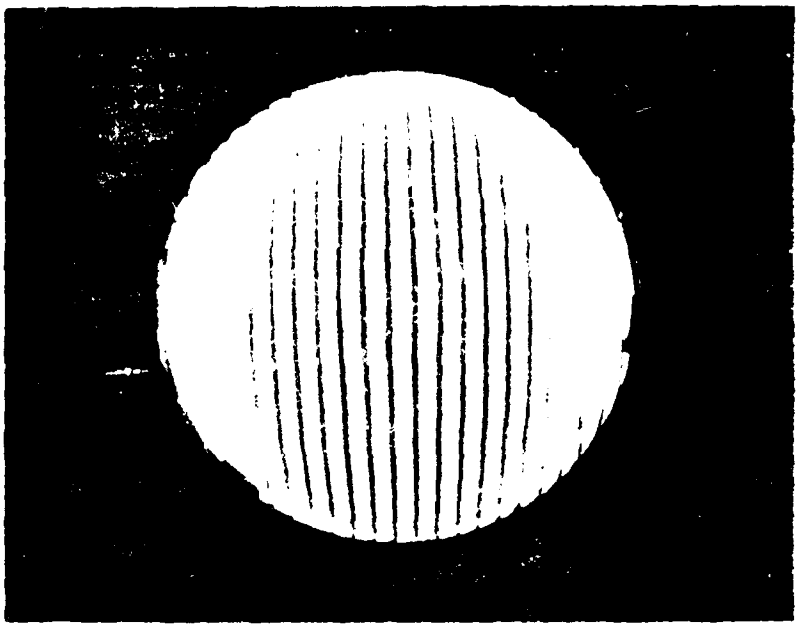


Figure 3.9 The same rulings in monochromatic light give the familiar fuzzy and ill-defined fringes as shown here, along with the point spread function of the ruling

Figure 3.10 Even at lower spatial frequencies, Ronchi Rulings give the same type of result as shown here

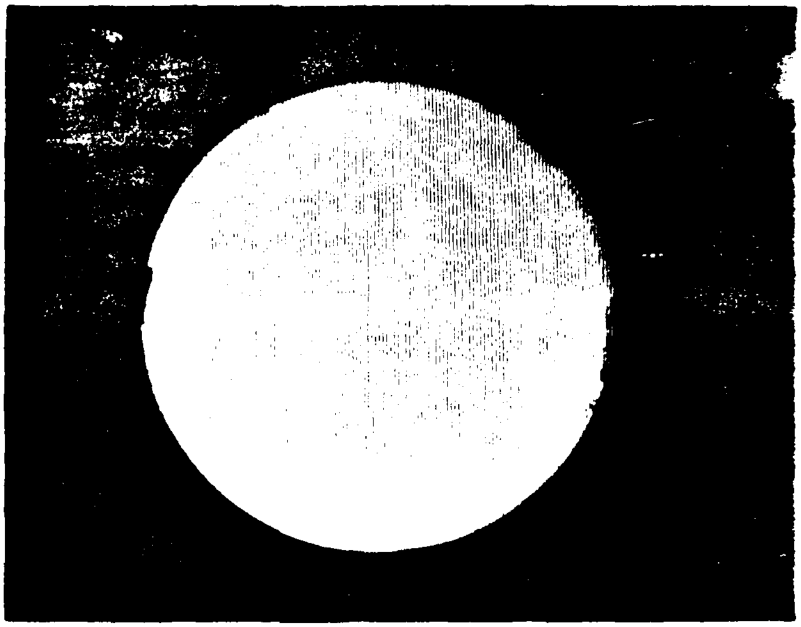


Figure 3.11 A sine wave ruling gives sharp fringes regardless of spatial frequency. Shown here is a high spatial frequency Ronchi test and characteristic three-point point spread function

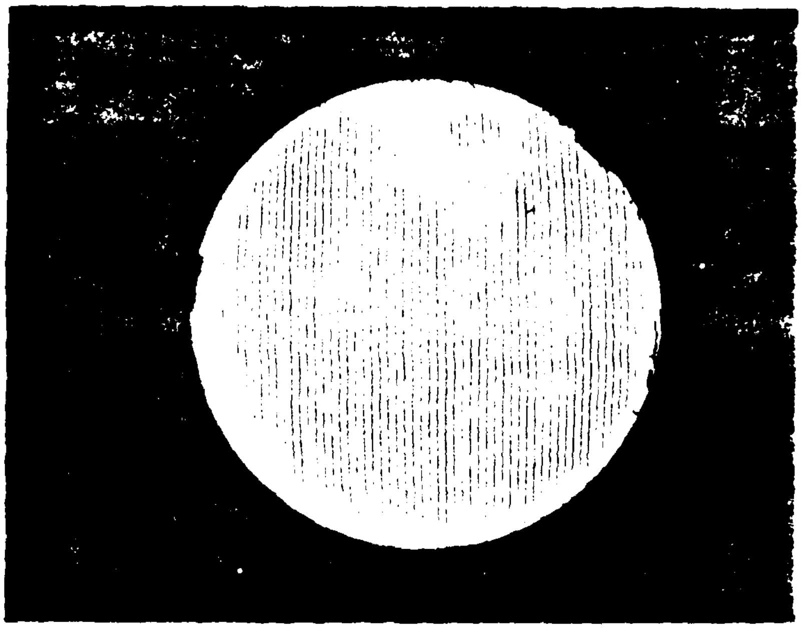


Figure 3.12 A medium spatial frequency Ronchi test with a sine wave ruling

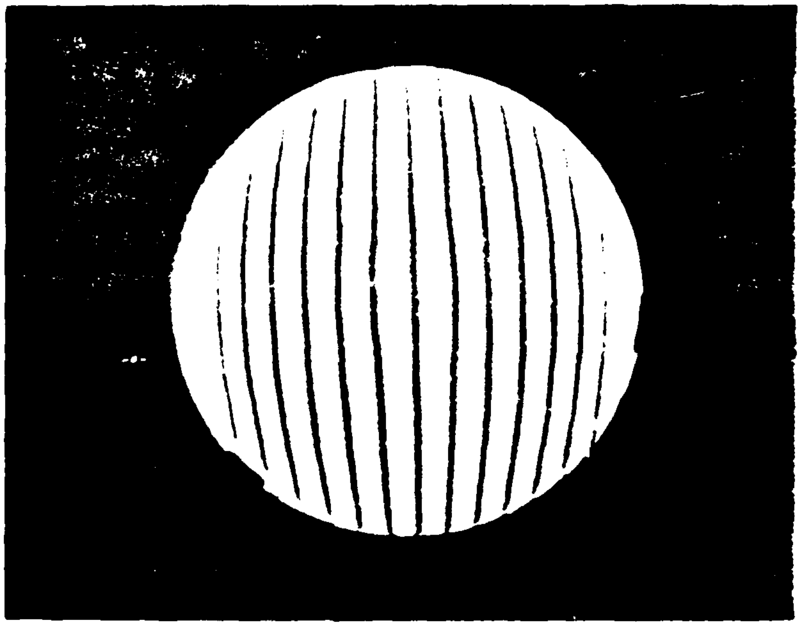


Figure 3.13 A low spatial frequency Ronchi test with a sine wave ruling

We conclude that a modified Ronchi test using a sinusoidal grating is both simple to use and adequate for quantitative analysis. If we were starting over, we would recommend this as the primary figure measurement technique. However, history (with the preprejudice that Ronchi tests are not quantitative) has favored other methods. In particular, good commercial Twyman-Green and Fizeau interferometers are available. Introduction of new competition (even of an inherently much simpler and reliable nature) seems less important than improvement of the ability of any of these systems to handle deep aspheres.

3.2 Surface Condition Testing

3.2.1 Existing Methods

The existing methods for studying surface roughness are mechanical (stylus), electrical (capacitive), or optical (speckle, total integrated scatter etc.). Of these, the stylus is the most popular and most accurate. Its accuracy is at least as good as that of the diamond turning process, so there might seem to be no need for other instrumentation. Unfortunately, that impression would be misleading. If what we want to do is to check the surface profile in a highly-localized area, a stylus instrument is quite adequate. If we want, instead, to examine the entireity of a large surface to determine the light scattering properties of each localized area, the stylus is clearly the wrong tool. Indeed the right tool does not exist.

Two failures of existing methods exist. First, they do not provide the spatial resolution that was our goal (see Section 1.2). Some, e.g. Strehl ratio, are measurements of the whole surface. Most, e.g. stylus, are so extremely localized that testing the entire surface is not only impractical (far too much time required) but also foolish (far too much data to analyze). Second, the parameters measured are not those of interest. What we really care about is how the surface scatters light. Even the best mathematician would find the scattering unpredictable in detail from the surface structure obtained with a stylus. He could, however, predict gross scattering behavior from a number average parameters (not just the average height).

Thus the measurements we make allow an imperfect prediction of scatter. If we want to control scatter, why not measure it? If we want to make spatially-localized measurements all across the surface, why not scan a probe beam across it? From these considerations, we have devised a special-purpose scatter monitor.

3.2.2 Scatter Monitor

The conceptual design of a scatter monitor which will locate and characterize surface defects on machined optics is described in this section. A prime objective is to accommodate a wide variety of optical shapes and yet by modular design, minimize the set up effort in switching from one surface shape to another. In addition to flexibility achieved through modular design, key features of the scatter monitor are summarized as follows:

1. Conjugate point centering
2. Variable scanning spot size
3. Spatial localization of defects
4. Image-wise display
5. Selectable defect criteria
6. Infrared and visible illumination.

The basic approach of this scatter monitor is to illuminate each point of the machined optical surface under test with a small spot of light whose principal ray is either normal to the surface or at the proper angle to achieve conjugate point centering. With a systematic raster or spiral pattern scan the entire surface is analyzed point by point. The scanning spot size can be varied (nominally 0.2 mm to 2.0 mm) to accommodate specific test requirements. Spot size will determine the spatial resolution of gross surface features while the statistical surface properties (texture and ultra fine machining marks) will be analyzed with only a weak dependence on spot size.

By mapping each point on the machined surface into a two dimensional plane corresponding to the exit pupil, spatial localization is outputted in terms of coordinate addresses (r and θ or x and y) with respect to the

optical axis. The signals used to drive the scanning spot are also used to scan a storage CRT spot to achieve image-wise display of the defects. A detector array is used to analyze the reflected scattered light from the test surface and the processed array output used in turn to both modulate the CRT beam and provide the classification of the defect. By controlling the processing codes of the raw detector output, the defect criteria can be made selectable (i.e. the scatter monitor is potentially smart and can be taught to recognize a wide variety of defects and textures). Finally, two illuminants (0.633 μm and 3.39 μm) are available for sequential use in the monitor, and while these optical sources (HeNe lasers) have a coherent output, the scatter image information is built up incoherently point by point. A special detector design incorporating lead sulfide for the long wavelength and an overlay of silicon for the short wavelength is specified to avoid the need for switching between two arrays.

An artist's concept of the scatter monitor is presented in Fig. 3.14 in which the modular approach is clearly recognized. A vibration isolation table is used to mount the optical components while the electronic display and control components could be remotely located. The heart of the scatter monitor, the source/detector scanner module, is depicted as the box in the upper left-hand corner of the table. The chief functions of this module are to provide a scanning beam of radiation that sweeps out a spherical surface and a detector that senses all retroreflected (specular and scattered) radiation. In general, two five degrees of freedom (x, y, z, θ, and ϕ) stages are employed to mount the test and auxiliary optical elements. Through the electronic control module selections are made of wavelength, spot size, and defect criteria. Image-wise presentation of the defects is then shown on the storage CRT while hard copy printout of the defect mapping is provided through computer interfacing.

Examining the Source/Detector Scanner Module in greater detail, we show an isometric sketch of the unit with its cover removed in Fig. 3.15. Simple lollipop mirror mounts were used to keep the sketch from being overly detailed, but in fact three point adjustable kinematic mounts would be used throughout the unit.

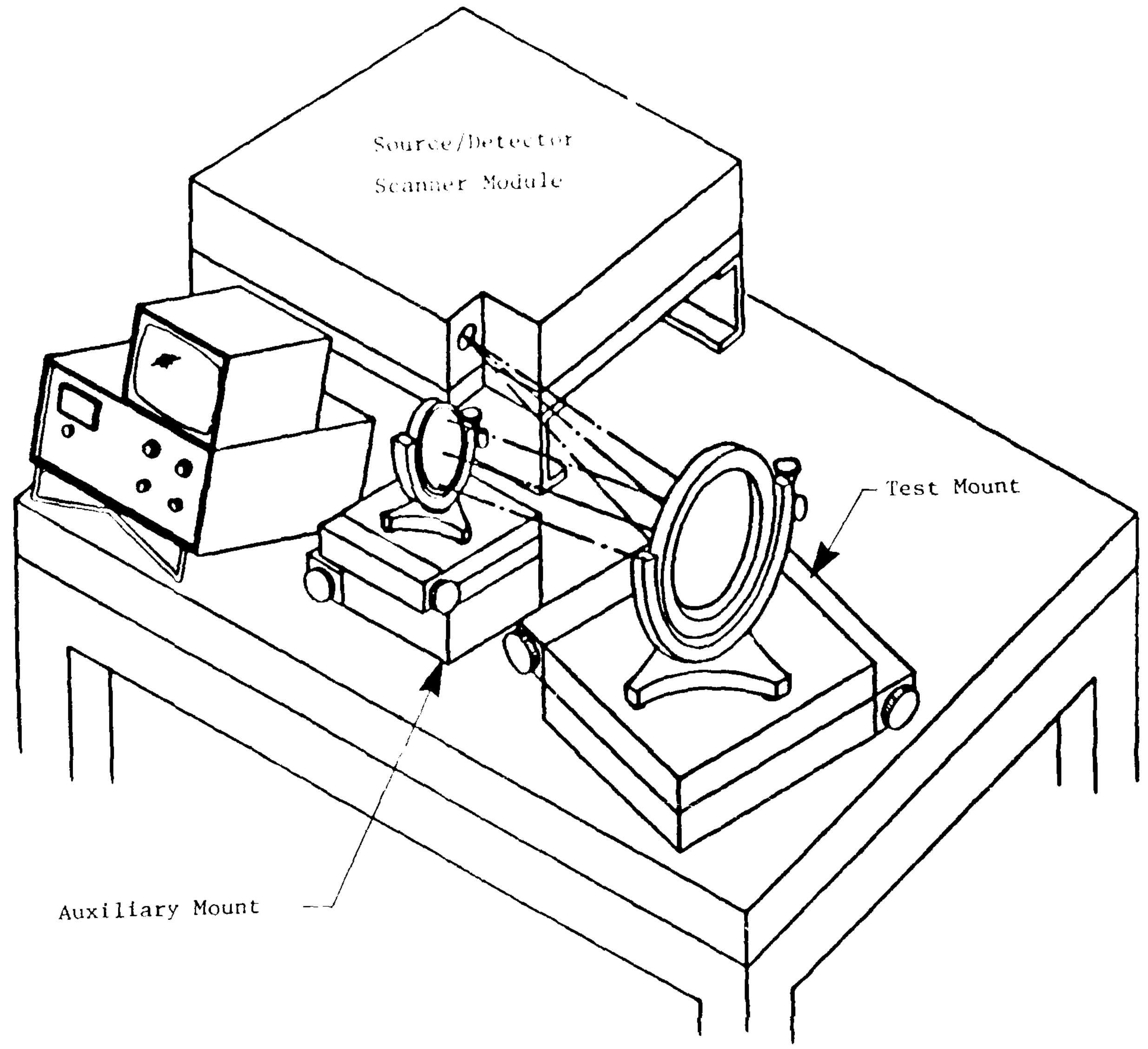


Figure 3.14 Artist's concept of the scatter monitor system

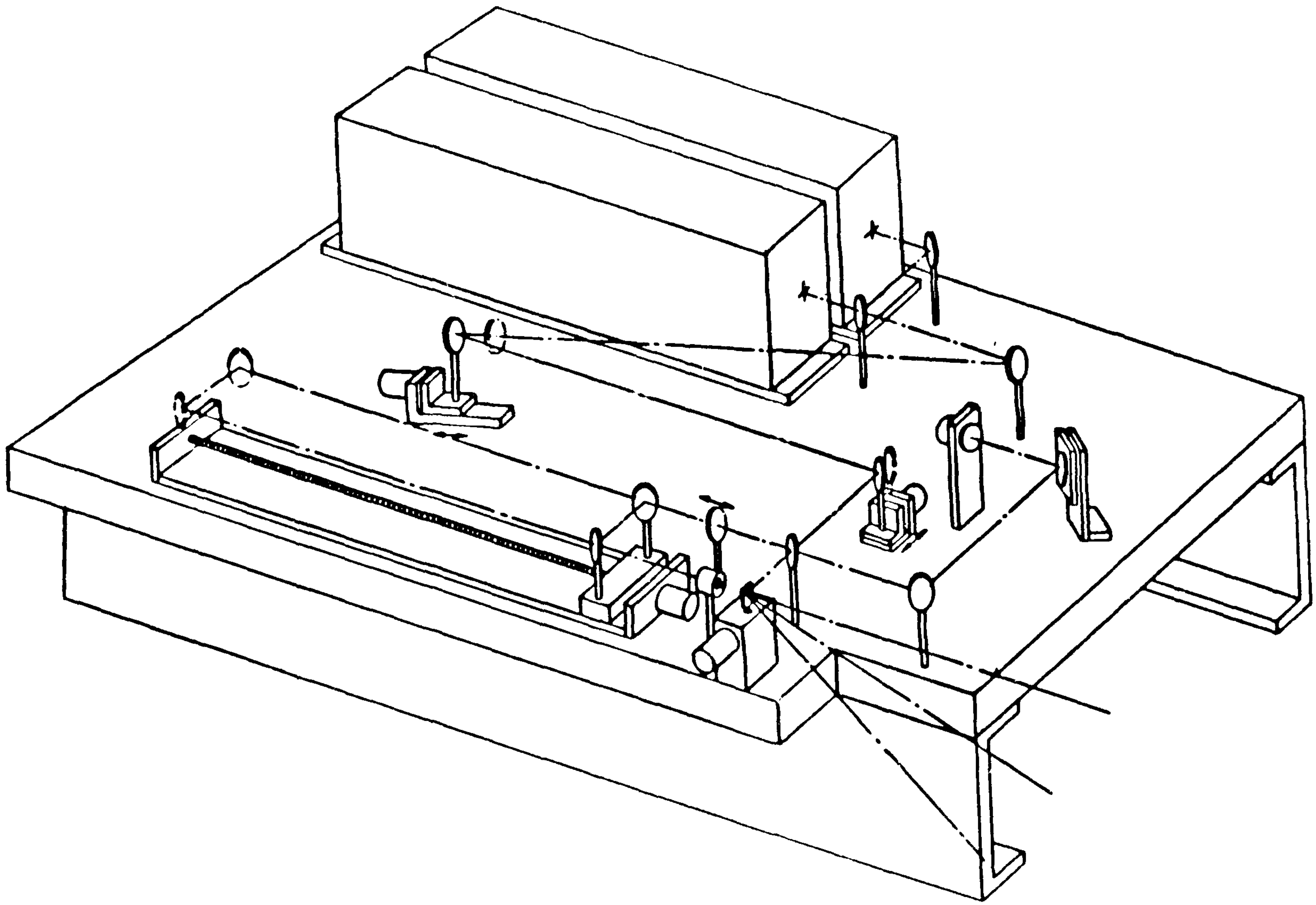


Figure 3.15 Isometric sketch of the source/detector scanner module

The five major subassemblies of this module can be more readily identified in the optical schematic of Fig. 3.16 as follows:

1. Laser Sources
2. Beam Combining And Spot Forming Optics
3. Optical Axis Tracker
4. Scanning Mirror
5. Scale Compensator
6. Gross Defect Detector

Both laser sources are helium neon, one visible and one infrared. A dichroic beam splitter is used to coaxially combine the output beams. The spot forming optics consist of two paraboloidal mirrors, the first of which is fixed and focuses the beams down to a spatial filter pinhole. From the pinhole the beams diverge until they are reflected by a second traveling paraboloidal mirror which focuses the beams onto the test surface which is at a large distance compared to the distance from the pinhole to the second mirror. To compensate for the lateral shift that occurs when the second paraboloid is moved, a correction is made by means of an optical axis tracker that controls a plane mirror to keep the beams on a fixed optical axis. The tracker servo loop consists of a beam splitter, two mirrors, a quadrant detector whose center is established (i.e. is made coincident with) the optical axis, a servo amplifier and the mirror with drive motor. The tracker subsystem insures that the beams are properly fed to the mirror scanner as beam focus is changed to achieve various scanner spot sizes.

The mirror scanner has two orthogonal rotation axis which pass through the optical axis and which lie in the plane of the mirror surface. In the schematic representation of the mirror scanner in Fig. 3.17 notice the beam passes through the horizontal bearing axis.

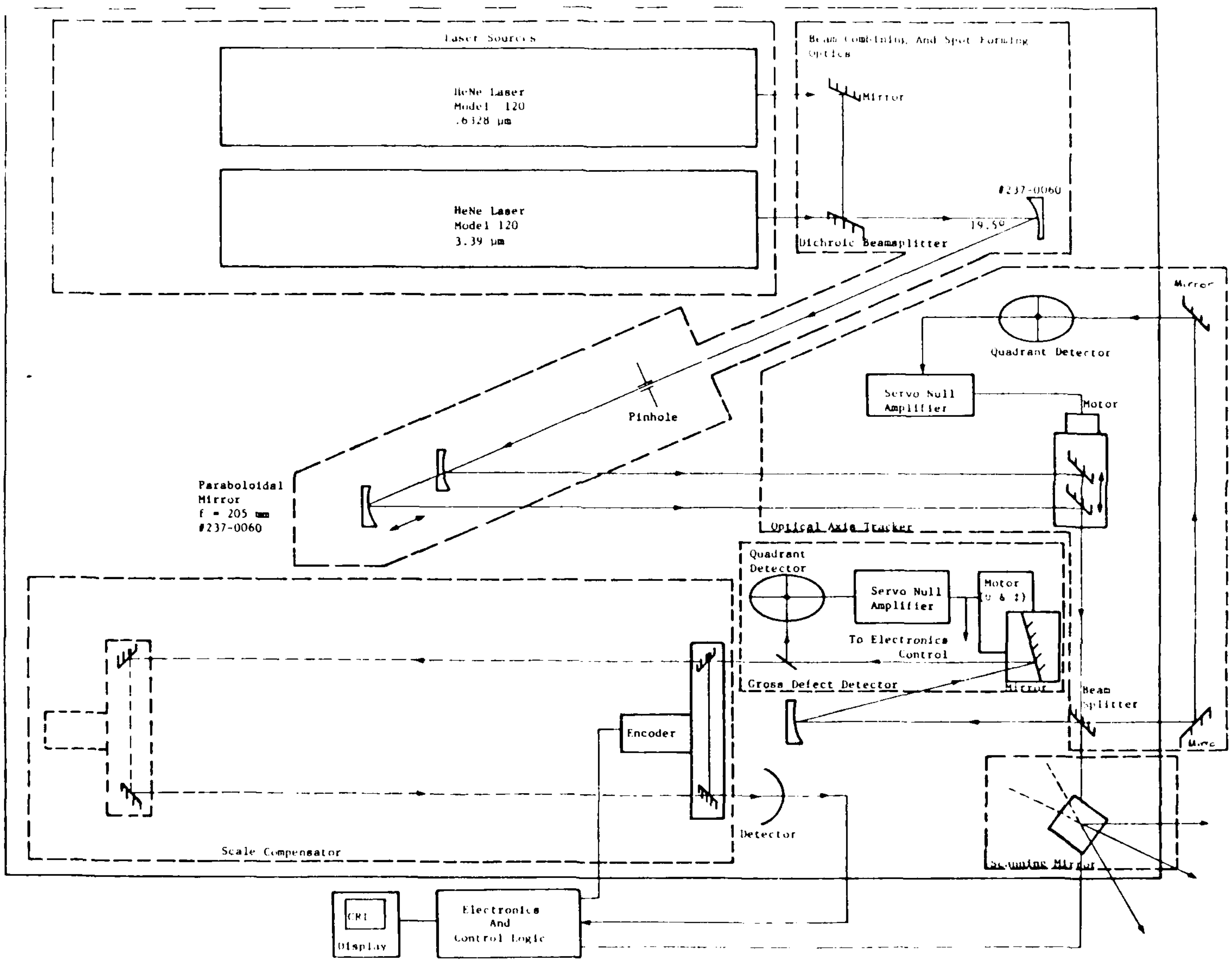


Figure 3.16 Optical schematic of the source/detector scanner module

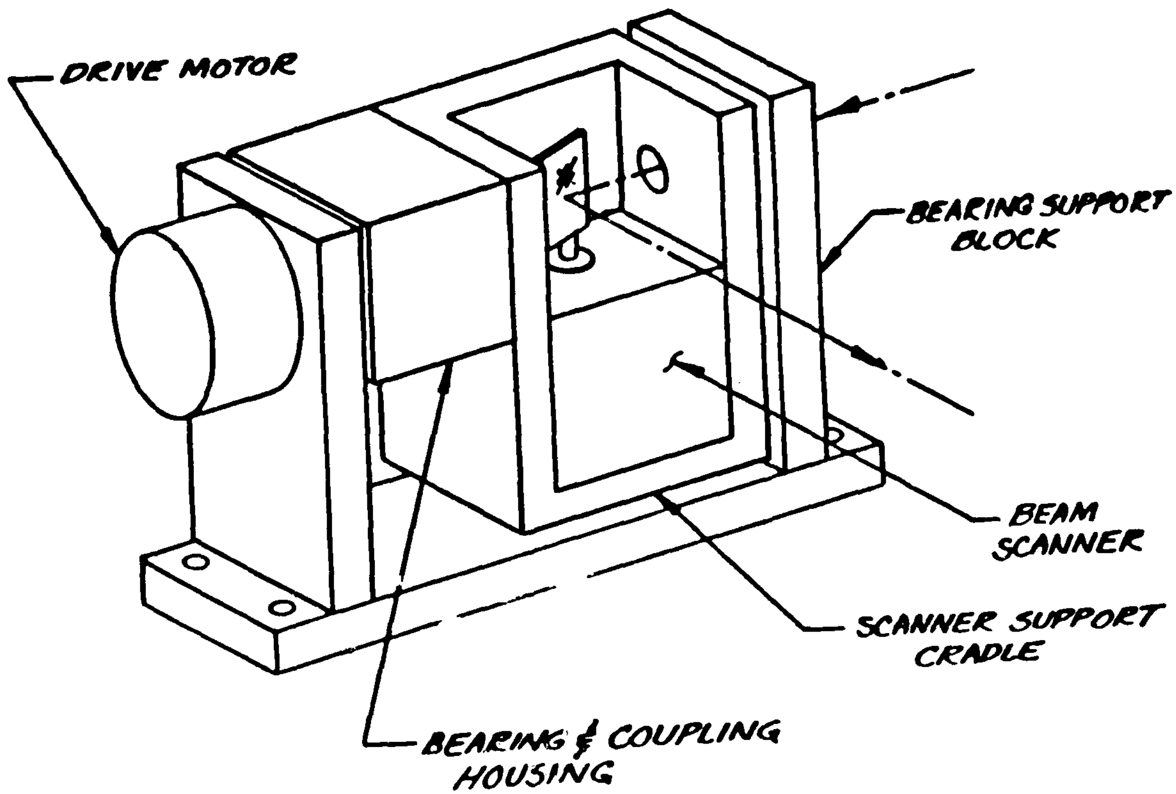


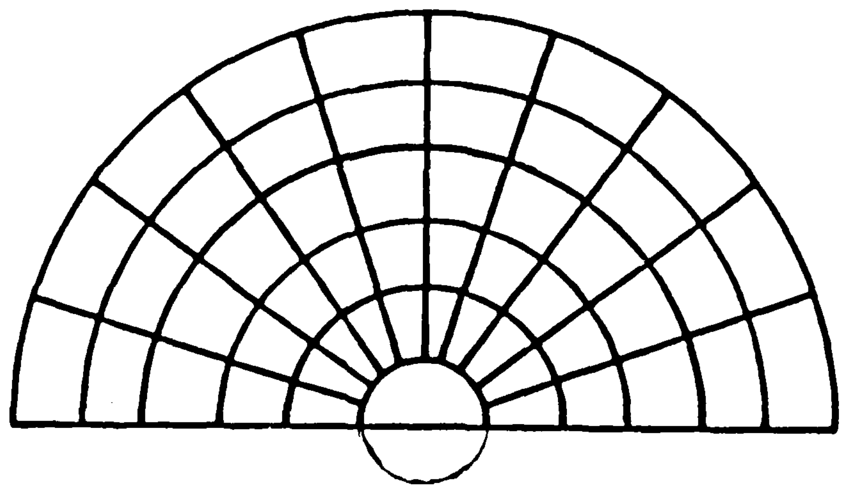
Figure 3.17 Two axis mirror scanner

The horizontal axis is rotated through a bearing and coupling housing at a relatively slow speed (i.e. about 1/500th that of the vertical scan axis) while the vertical axis is rotated by a higher speed (commercial) scanner. For standard TV compatability the vertical scanner which produces the horizontal sweep must cycle 525 times for each vertical sweep by the horizontal scanner. The point at which the optical axis intercepts the two rotational axis is the origin of the spherical cap swept out by the beam. This point acts in many respects as a point source from which eminates a spherical wave. Of course since the two rotation angles are limited, only a segment of the spherical surface is scanned out.

In the lower right hand corner of Fig. 3.16 we indicate that each beam is either retroreflected back on itself or on a complementary beam by the test and auxiliary optics as a result of conjugate point centering (specific examples will be given later). Thus the principal ray of each beam is reflected back through the scan mirror origin and then back along the optical axis to the beam splitter where a fraction of the return beam is reflected to the left into the relay optics. The relay optics are specified as reflective elements so that focus is the same for both visible and infrared illuminants. The relay optics images the spatial spectrum (i.e. Fourier Transform) of the return beam onto the detector array through both the scale compensator and gross defect detector subassemblies. The compensator maintains the scale of the spectrum constant on the array as various focal length test optics are evaluated in the monitor. Keeping the spectrum scale constant insures that the defect criteria are not altered by a change in focal distances.

Since the scatter spectrum will always be symmetric, the detector array need only cover 180° of the spectrum plane. In Fig. 3.18 we show the geometry of a 51 element array that readily lends itself to reducing and interpreting the scatter spectrum. The central circular element is placed on the optical axis and intercepts all the unscattered (dc) specularly reflected scanning beam. The larger the percentage of reflected light falling on this central element, the more perfect and scatter free the surface point under test.

DETECTOR GEOMETRY



51 ELEMENT ARRAY

Figure 3.18 Detector Array (51 Element)

The more light falling on the detector segments displaced further from the optical axis the greater the scatter angle that was impressed on the reflected light. From this data we can determine the typical texture correlation length and relief depth. Integrating the ten outputs of each semi-annual ring set provides convenient data for spatial frequency analysis while integrating the five outputs of each wedge segment provides data for analyzing azimuthal characteristics of the scatter.

The PbS detector response (peak at 1 KHz) sets the basic limitation on the time required to scan one frame. Using standard TV format of 525 lines/frame and assuming a 525 point/line resolution, the minimum scan time per frame (275,625 points) is just under five (5) minutes. If frames of greater space-bandwidth are required (e.g. 1050 lines/frame) then the scan time will increase proportionately with the total number of points in the frame.

The last subassembly of the scanner module works in conjunction with the detector array and a second quadrant detector. A gross defect on the test surface will not only cause the reflected beam to be scattered but will also cause the principal ray to be displaced from the optical axis (i.e. the central detector disk). The function of the gross defect subassembly is to bring the principal ray back onto the optical axis by means of a quadrant detector, servo amplifier, and two axis deflection mirror. The magnitude and direction of the correction signal applied to the mirror is a measure of the defect's surface normal. This signal is also displayed on the CRT but with flags to distinguish it from surface texture information.

In Fig. 3.19 we indicate the simplest test setup for a concave spherical mirror. Retroreflection is achieved by placing the test optical surface at 2f (i.e. 1:1 conjugates) from the scanner center. Similarly the setups for other specific optical shapes are shown in Figs. 3.20 and 3.21. The surface designated as "test" can alternately be considered the "auxiliary optics" and vice versa. In these examples each ray retraces itself. However, in Fig. 3.22 we give an example of how an aplanatic surface can be handled in which only the principal ray retraces itself but all other rays retrace on complementary paths.

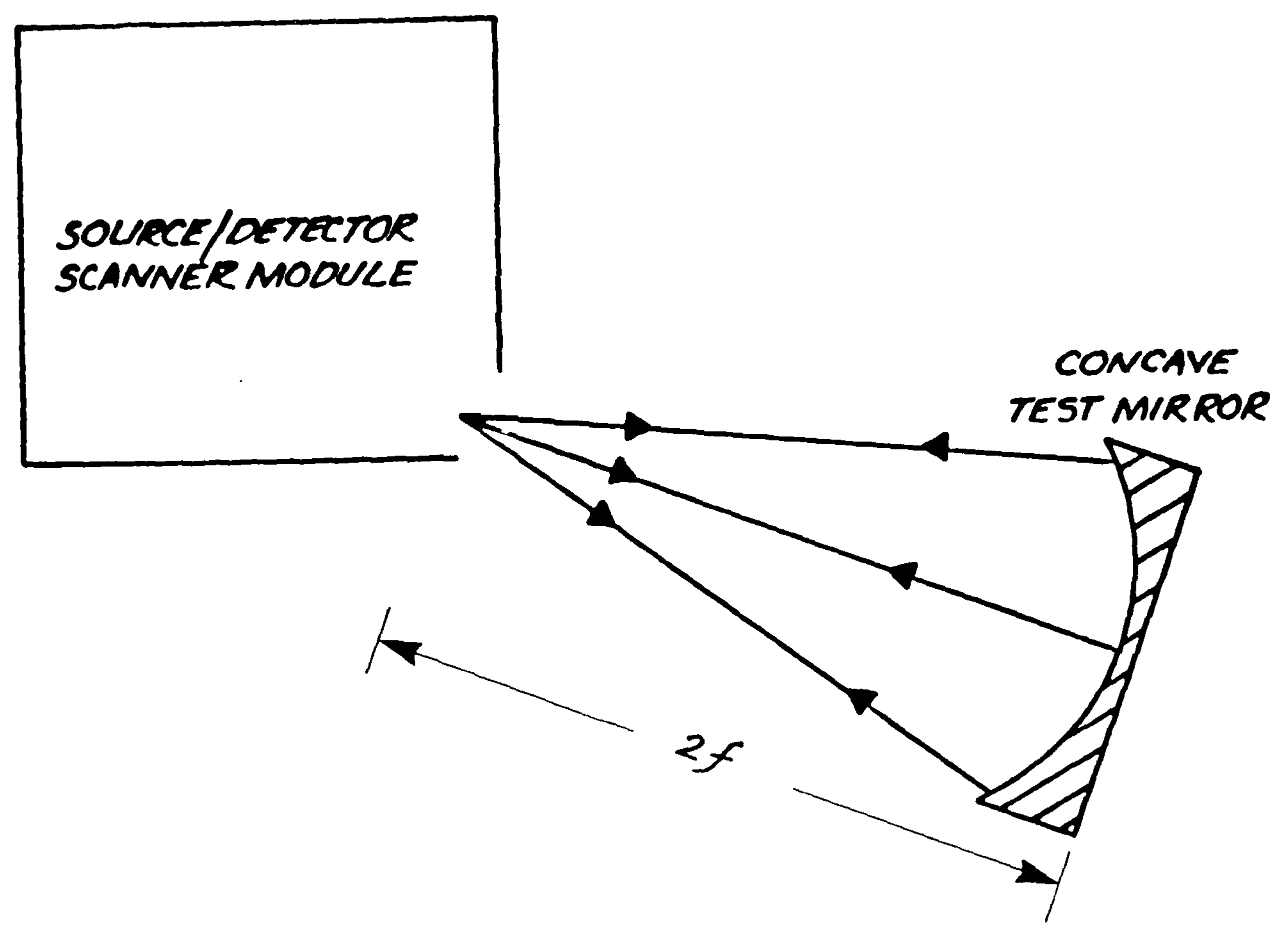


Figure 3.19 Conjugate point set-up for concave spherical test mirror

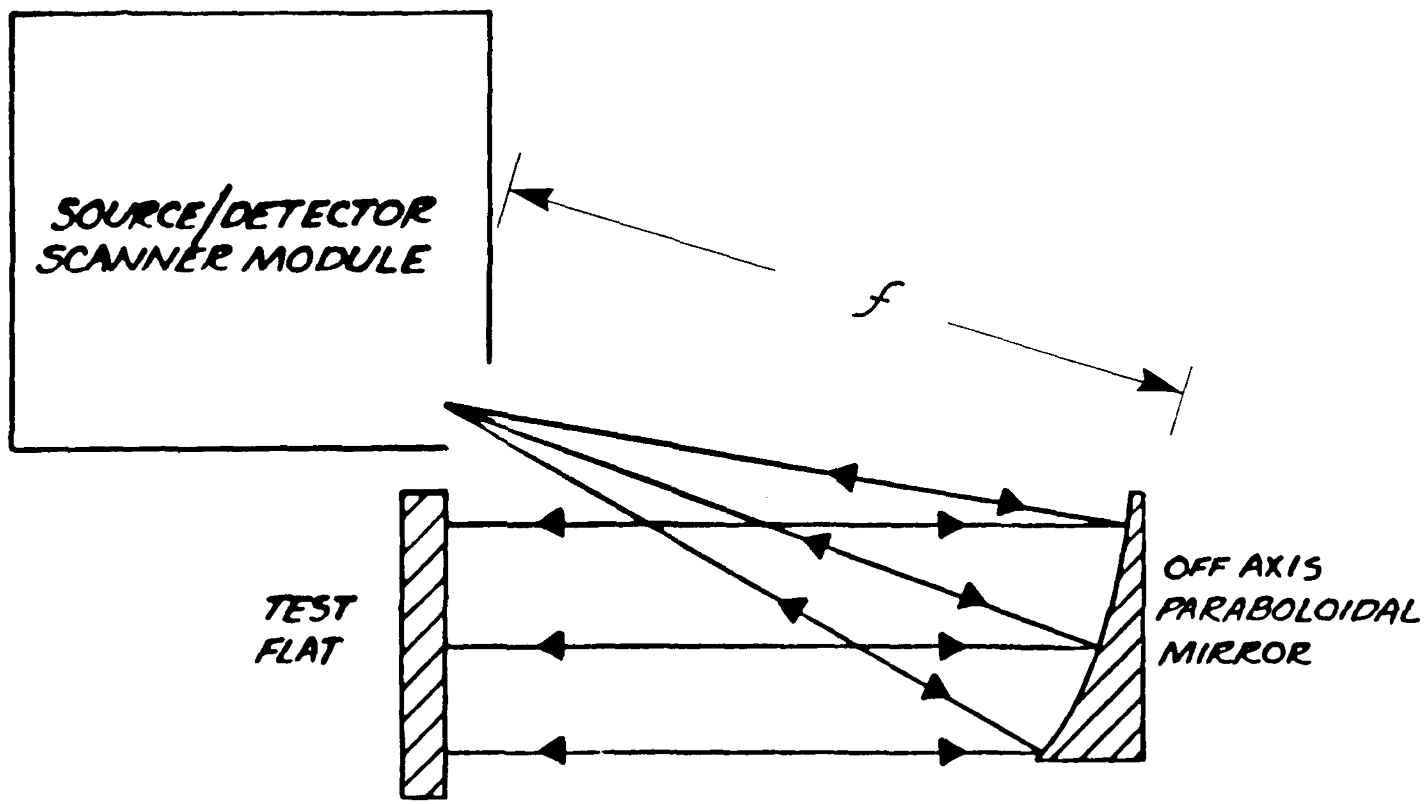


Figure 3.20 Conjugate point set-up for off-axis paraboloidal and flat test surfaces

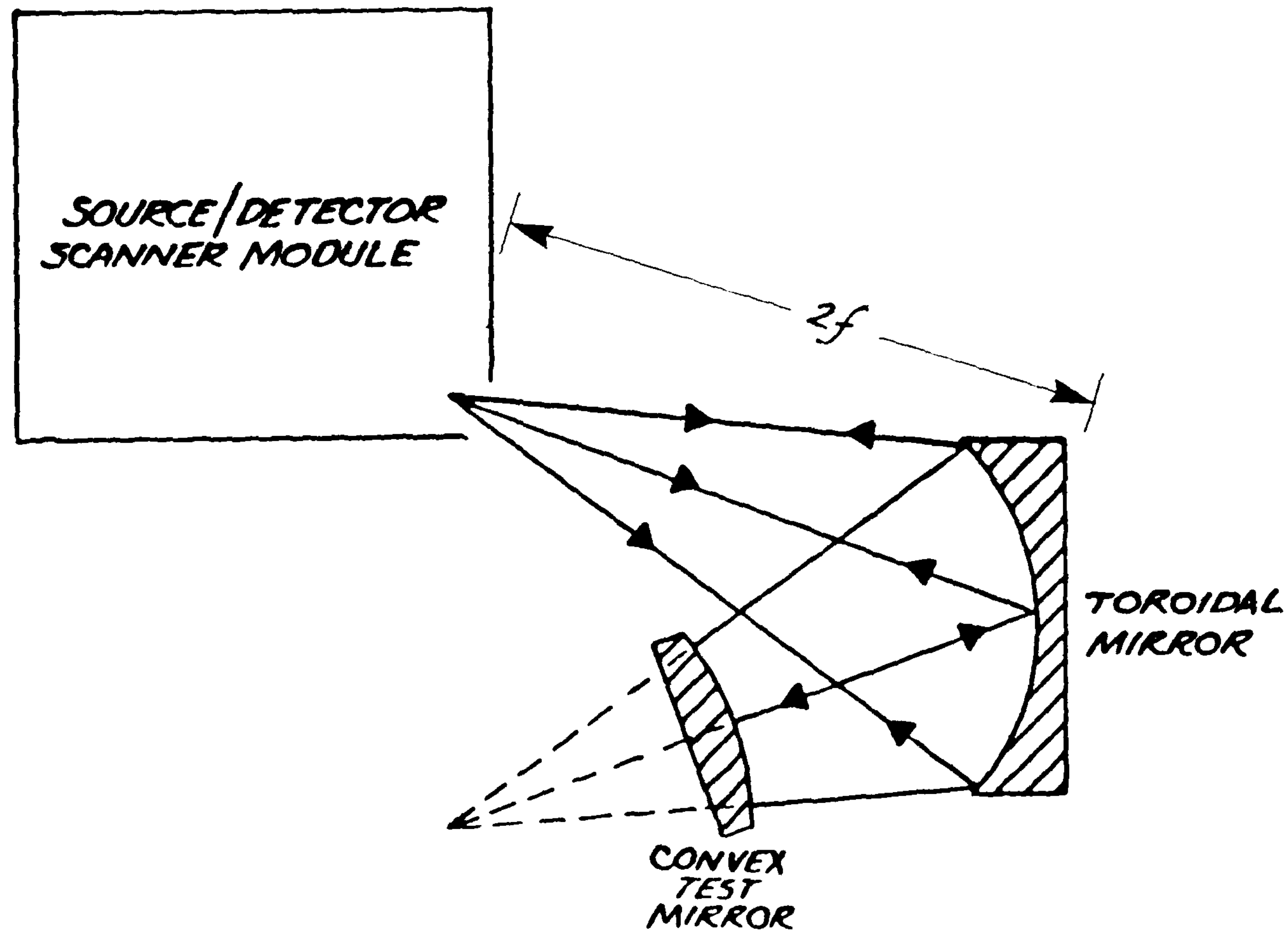


Figure 3.21 Conjugate point set-up for toroidal and convex test surfaces

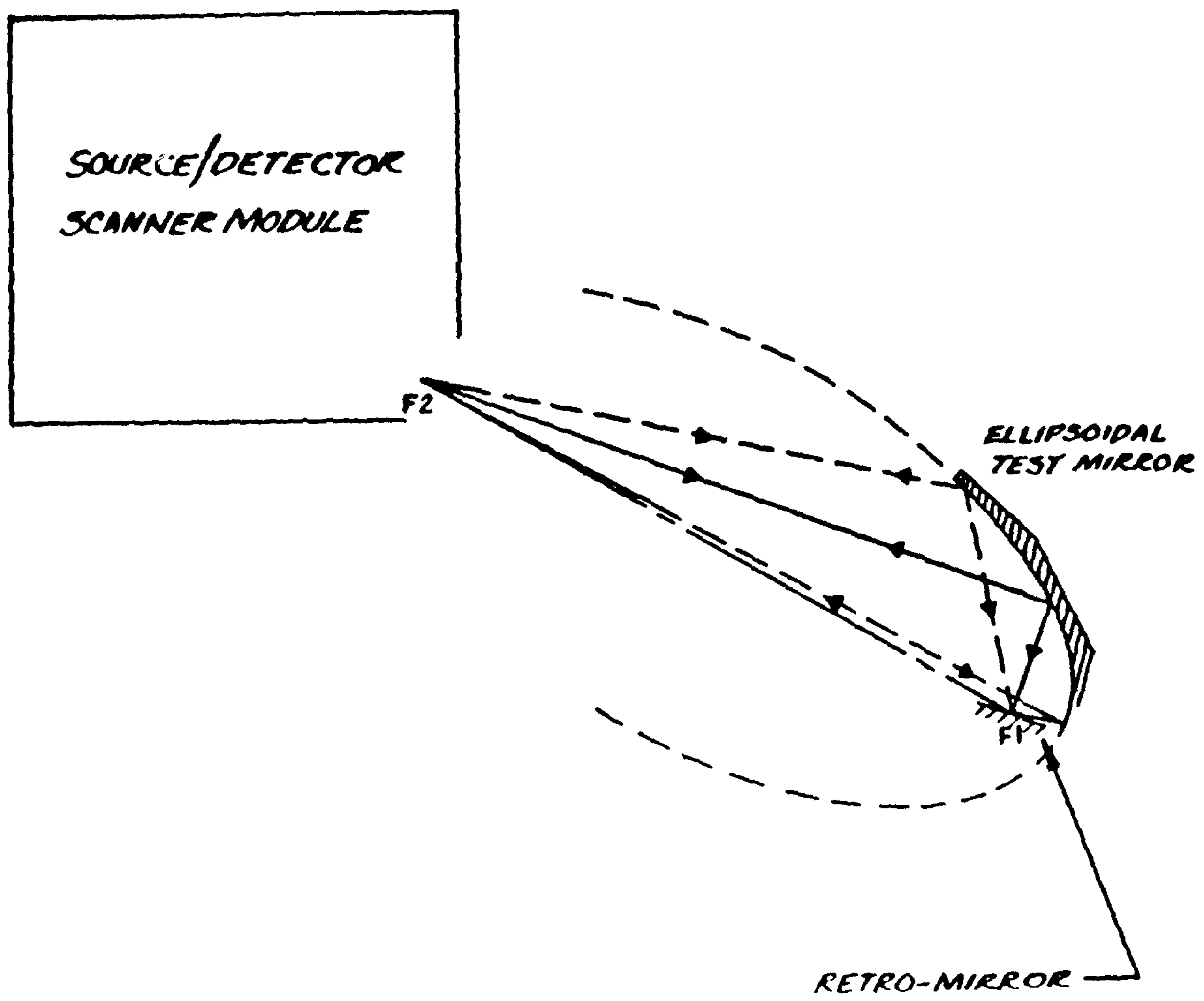


Figure 3.22 Conjugate point set-up for ellipsoidal test surface

The scanner center is placed at one of the ellipse's focuses while a plane retro-mirror is placed at the other focus point.

In general, only two sample holding stages (one for the test element and one for auxiliary optics) are required for all the various conjugate point centering setups and this simplifies alignment and tracking considerations. On the other hand the scatter monitor is not a "black box" into which the test optics are dropped and out of which the surface analysis is automatically displayed. Some skill and training in optical alignment techniques as well as a complete understanding of the device's capabilities are required on the part of the operator. If a large number of nominally identical test samples are to be analyzed, then after the initial setup has been completed, subsequent samples could be tested by a technician of lesser skill who would only have to master mounting, data taking and dismounting techniques.

3.3 Computer Generated Holograms

3.3.1 Motivation And Status

While classical interferometry is designed to compare a spherical surface with a spherical surface, it suffices for handling shallow aspheres if the data is analyzed properly. To handle general aspheres, computer generated holograms have been suggested. These can convert the spherical wavefront from the reference beam into the form it would have if the mathematically ideal surface were present in the interferometer. In a massive study of this technique, Loomis [3-9] showed that to test a surface with F fringes deviation from the reference beam to a λ/N accuracy, we need to write at least

$$P = 4FN \tag{3-22}$$

points along each line of the hologram. Choosing modest values like $F = 200$ and $N = 20$ leads to the requirement of $P > 16{,}000$. Present hologram writers are capable of $2000 \lesssim P \lesssim 4000$.

Clearly we can do almost as well with classical interferometry without a hologram. What is needed is the capability of writing holograms with 20,000 or more points per line. Writing 20,000 points is not hard, but writing them where we want them to the required accuracy is hard.

3.3.2 Hologram Writing System

Aerodyne Research, Inc. has designed a hologram writer which can be used to write meaningful holograms in a reasonable time. We describe the basic scheme here.

3.3.2.1 Objective

The objective of this task is to develop a prototype facility for generating synthetic holograms for use as wavefront correctors in testing deep aspheric optics. The optics under test are generated by diamond turning techniques and their ideal shape and wavefront characteristics are known in terms of the computer design program used to command the three dimensional machining operation. The holograms to be computer generated will have the appearance of interferograms and be described in terms of a binary spatial function. In operation the holograms will modulate the wavefront phase and leave the amplitude constant.

3.3.2.2 Approach

The approach is to use the computer design information of the optical component under test to calculate the hologram function. From the hologram function, a series of commands are prepared to control an optical writing device in which a photosensitive plate is exposed. After photographic processing, the exposed plate yields the desired wavefront correcting hologram which can then be used in a conventional interferometer to evaluate the test component. The specific interferometer test setup must also be taken into consideration when calculating the hologram function.

The optical writing device consists of an x-y step and repeat stage that translates the photosensitive plate, a high resolution precision CRT

on which segments of the hologram function are displayed, an optical reduction system that images the CRT output onto the photosensitive plate, and interface electronics that put the CRT pattern generation, x-y stage translation, and plate exposure under computer control. High mensurational accuracy is achieved by using the interferometer tracking data to generate an error signal between actual and nominal stage position. Instead of trying to correct the stage position, the error signal will be used to shift the CRT output to compensate for stage error.

3.3.2.3 Design requirements

The number of fringes to be compensated by the hologram can be estimated on the lower limit to be 25 fringes (12.5λ) since conventional fringe analysis techniques are still practical for that number. In a sense there is no upper limit on the number of fringes to be corrected, since deep aspheres could depart drastically from a spherical reference surface, but by using "near sphere" or "near conic" techniques the number of fringes could probably always be held to no more than several hundred and so we will somewhat arbitrarily choose 500 fringes as our upper design limit.

The number of lines to be printed on the hologram is given by

$$N = 4FL$$

where λ/F is the fractional wavelength sensitivity desired in the hologram and L is the maximum number of wavelengths between the reference and test surface. Conventional interferometer accuracy is 1/20 wavelength for plano and 1/10 wavelength for spherical testing over a 100 mm clear aperture at λ = 632.8 nm. By setting a design goal of 1/200 wavelength accuracy for the lower limit fringe number, and working with a 100 mm x 100 mm hologram aperture, the spatial resolution requirement on the hologram reduces to

$$\omega_o = \frac{N}{W} = \frac{4(200)(12.5)}{100\ \text{mm}} = 100\ \text{lines/mm}$$

where W is the hologram aperture size.

Writing at a frequency of 100 lines/mm requires a good but not a particularly sophisticated or sensitive optical system. On the other hand, if the line frequency is held constant, then wavefront accuracy will decrease linearly with the number of waves corrected. At the upper limit of 500 fringes (250 wavelengths), the accuracy drops to

$$1/F = 4L/N = 4L/\omega_o W = 4(250)/100 \text{ lines/mm } 100 \text{ mm} = 1/10.$$

If higher accuracy is required together with large path length correction, then the writing frequency could be increased to 200 lines/mm with a corresponding accuracy of 1/20 wavelength for 500 fringe correction.

To maintain positional accuracy to 1% at 100 lines/mm requires 0.1 micrometer resolution in the x-y translation stage. Also, if we compose each hologram line from 10 CRT raster lines, then each raster line must not wander more than 10% off its width. Typically we might use a 2000 line x 2000 line CRT reduced to yield 1000 CRT lines/mm or 100 hologram lines/mm (though the CRT lines would not necessarily have to be resolved). At this reduction size, the hologram would be composed of a 50 x 50 array of 2 mm x 2mm cells. Allowing between 1 sec. and 4 sec. exposure per cell, total writing time would run from 3/4 hrs. to 3 hours per hologram.

3.3.2.4 Step and repeat writer description

We have already referred to various components of the step and repeat writer and they can be listed by function as follows:

1. Main frame structure,
2. x-y translation slides with stepper motors,
3. Two axis plane mirror interferometer,
4. CRT pattern display,
5. Optical reduction system,
6. Electronics interface,
7. Computer controller.

An artist's concept of how these components might be configured is shown in Fig. 3.23. The main frame structure consists of a vibration-free air isolation table with a granite slab, a massive base plate for mounting the x-y slides and interferometer and a vertical yoke assembly for mounting the CRT and optical reduction components.

The x-y stages each have 125 mm travel, with 1 micrometer positional accuracy and repeatability when translated by their precision stepper motors. Various stepping increments from 1 micrometer to 25 micrometer and various stepping rates from 1000/sec to 10,000/sec are available. Stages meeting these specifications can be supplied by Klinger Scientific Corporation.

The laser interferometer will have a resolution of 0.08 micrometers with the option of being extendable to 0.008 micrometers, and with an accuracy of ± 0.5 parts per million. A suitable interferometer is the Hewlett-Packard Model 5501A with appropriate receivers, beam benders, beam splitters and plane mirror interferometer modules. Included with the interferometer are interface and metric unit pulse output electronics. The interferometer provides the basis for the high mensurational accuracy of the system. We regard the x-y stages and stepper motors as providing coarse positioning and the interferometer as providing fine position correction signals.

Standard precision high resolution CRT systems are available in 5 inch diameter with 2500 lines of 2 mil width and 0.25% linearity. Brightness uniformity can be held to ± 5%. Special compensating circuits are used in these systems to eliminate distortion. Infotex Inc. is one supplier of this type of CRT system. The CRT permits great flexibility in pattern generation and provides a convenient means for compensating x-y table position errors.

The optical system for a 2 mil line width CRT should operate at about 51:1 to achieve 1 micrometer stroke width. Each CRT line image need not be resolved on the photosensitive plate (in fact it would be better if it were not since it would only introduce undesirable high frequency diffraction components). On the other hand, care must be taken in selecting the optics to minimize distortion and at the same time maximize image brightness.

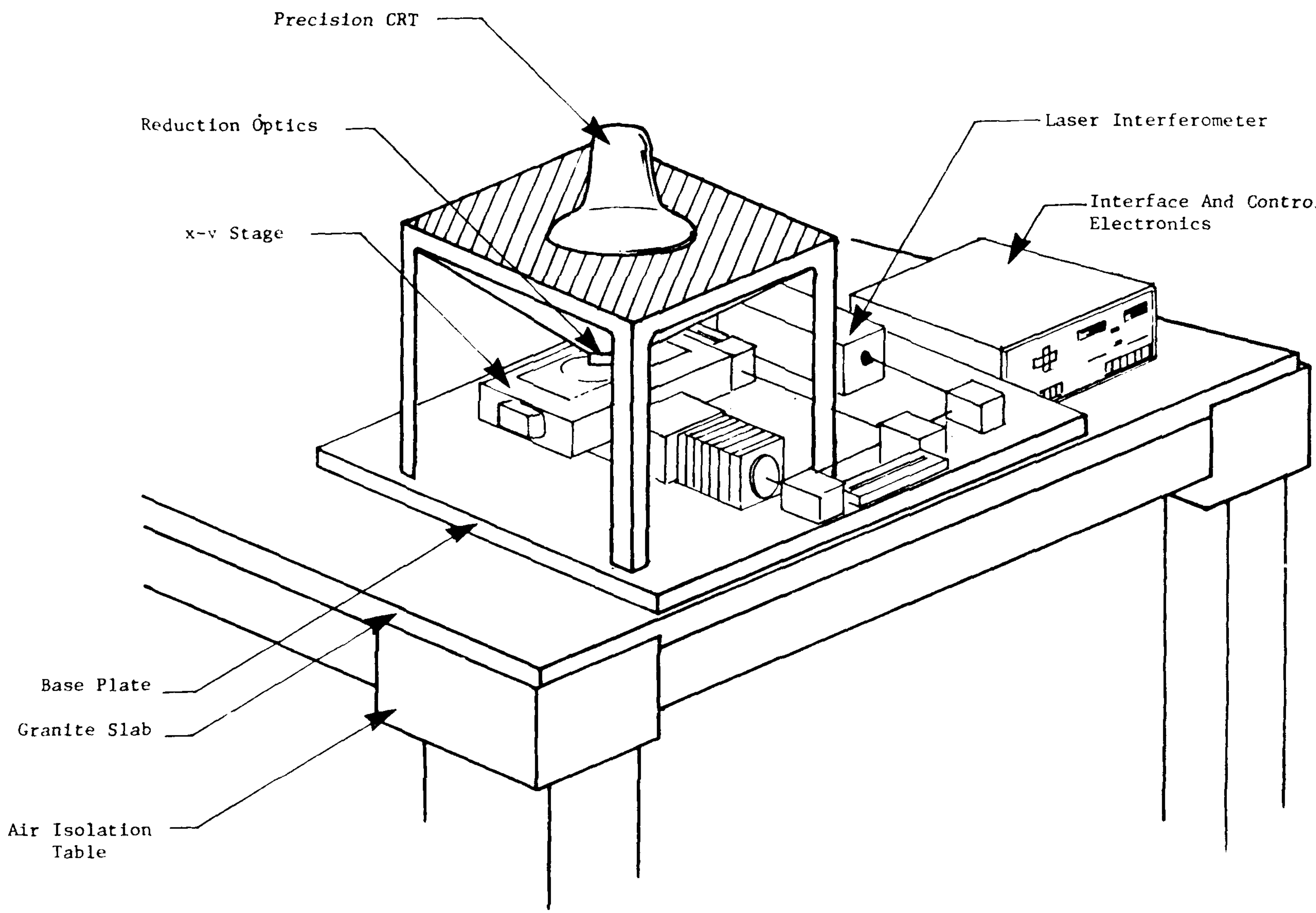


Figure 3.23 Artist's concept of the step and repeat writer

Flat field microscope objectives should be suitable for this application.

Interface electronics will be required for driving the x-y stepper motors, reading the interferometer pulses and modulating the CRT scanning spot. And finally, a dedicated minicomputer will be required to control all of the system functions and sequences. The hologram function would be calculated off-line but the writer executed commands would be recorded on disk and subsequently used by the computer to generate the synthetic hologram.

3.4 References

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3.2 Figler, B. D., "Precision Focus Control", SPIE Proceedings, Vol. 141, Adaptive Optical Components, 1978.

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4. RECOMMENDATIONS

4.1 Introduction

The government can undertake several tasks which would aid the specification, manufacturing, and acceptance testing of machined optics. We will discuss each in what we believe to be its order of importance.

4.2 Computer Generated Holograms

Holographic testing for deep aspheres has been demonstrated by many people. To date, the technique is severely limited because the number of resolvable elements that can be written by a computer controlled plotter is excessively small. A new technique developed by Aerodyne Research, Inc. can remove these limitations and thus allow holographic lens testing to be used at high accuracy for deep aspheres. Developing this is by far the most important thing the Government can do to aid in the testing of machined optics.

4.3 Scatter Monitor

Developing such an instrument on the basis of the design of Section 4.2 would be straightforward and only moderately expensive. Subsequent units would cost less than half the development price.

4.4 Nonconjugate Interferometry

For some tasks this is very important. In our judgement this requires a development effort preceding system construction. Thus it requires a multi year effort. Both the geometry and the interferometer were designed in this work.

APPENDIX A

PAPER ENTITLED:

"OPTICAL TESTING METHODS - A SURVEY OF EXPERTS"

OPTICAL TESTING METHODS
- A SURVEY OF EXPERTS -

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INTRODUCTION

This paper reports the results of an informal survey of experts in optical testing. The 41 respondents were given criteria by which they were to judge various testing methods for figure and surface condition of reflective (largely diamond-turned) optical surfaces. We found the results so interesting, that we wanted to abstract them for a wider audience. The respondents were generous with their time and advice. This would lead us to change the survey if we ever repeated it, but we doubt that the changes would affect the conclusions very much.

We know of one somewhat similar survey by De Vany (1), so we will compare conclusions with it after our response summary.

CRITERIA

We explained certain criteria for judging each test method and asked our respondents to rank each method with respect to each criterion. We will present the response matrix later, but now we must explain the criteria.

The five criteria were (1) surface specification, (2) flexibility, (3) interpretability, (4) simplicity, and (5) acceptability. "Surface Specification" was inserted to exclude global performance testing (e.g. optical transfer functions). We want to locate and describe local defects. "Flexibility" meant that an ideal method would work on single to multiple surfaces, reflective to refractive, visible to infrared, polished to diamond turned, imaging to nonimaging, etc.

"Interpretability" means quantitative meaning as well as simple intuitive meaning readily available to technicians. "Simplicity" was intended to allow use in laboratory, optical shop, and field environments and allow low cost, easy-to-use systems. "Acceptability" is the ability of the system to win widespread support in the optics community. A quick glance will convince the reader that some of these criteria are mutually antagonistic. For example, flexibility and simplicity are often opposed. As no present system satisfies the first four criteria, a new system would have to win acceptability (criterion 5). Therefore tradeoffs are an absolute necessity in any system design.

RESPONSE MATRIX

The responses can be viewed as a three-dimensional matrix: criterion, method, goodness of method. We have chosen to present the results as a criterion-method plot with the "goodness" votes shown at each intersection. The goodness was "quantized" as follows:

E - Excellent

A - Acceptable

P - Poor

U - Unknown, no vote.

The figure testing and surface testing results are shown in Table 1 and Table 2 respectively. The methods chosen were not all in the same logical category. Thus, for example, holographic methods (which can supplement several interferometric methods) is listed as a separate method to guarantee comment on it.

Table 1

LENS TESTING SURVEY

E	Excellent	P	Poor
A	Acceptable	U	Unknown

PART ONE: FIGURE TESTING

SUMMARY OF REPLIES RECEIVED

Criterion	Method									
	Newton, Fizeau, etc.	Twyman-Green, LUPI, etc.	Shearing Interferometers	Focault, Wire, etc.	Burch, Smartt, etc.	Ronchi, etc.	Hartmann, etc.	Star	Holographic Methods	Moire, Two-Wavelengths etc.
Surface Specification	20 E 11 A 5 P 1 U	27 E 10 A 1 P	8 E 21 A 6 P 1 U	5 E 19 A 15 P 1 U	10 E 12 A 4 P 6 U	3 E 19 A 12 P 2 U	4 E 13 A 15 P 2 U	4 E 7 A 20 P 4 U	13 E 13 A 2 P 6 U	10 E 10 A 10 P 7 U
Flexibility	7 E 14 A 14 P 1 U	23 E 14 A	6 E 22 A 4 P 1 U	8 E 17 A 11 P 2 U	6 E 14 A 6 P 7 U	8 E 17 A 11 P 2 U	3 E 14 A 14 P 2 U	13 E 5 A 13 P 3 U	12 E 13 A 4 P 6 U	4 E 14 A 9 P 6 U
Interpretability	26 E 9 A 3 P 1 U	29 E 10 A 1 P	3 E 13 A 19 P 1 U	4 E 16 A 16 P 1 U	13 E 13 A 2 P 6 U	3 E 22 A 11 P 1 U	4 E 9 A 19 P 2 U	6 E 8 A 18 P 3 U	12 E 14 A 5 P 4 U	6 E 16 A 8 P 6 U
Simplicity	19 E 6 A 1 P 1 U	7 E 23 A 9 P	5 E 25 A 5 P 1 U	26 E 7 A 3 P 1 U	14 E 10 A 2 P 6 U	23 E 12 A 5 P 1 U	6 E 12 A 13 P 2 U	17 E 12 A 2 P 3 U	1 E 10 A 20 P 4 U	2 E 13 A 14 P 6 U
Acceptability	27 E 7 A 2 P 1 U	28 E 9 A 1 P	4 E 19 A 11 P 2 U	14 E 19 A 4 P 1 U	6 E 17 A 2 P 7 U	7 E 21 A 8 P	2 E 14 A 15 P 2 U	7 E 17 A 9 P 3 U	4 E 14 A 11 P 6 U	6 E 8 A 16 P 6 U

Table 2

PART TWO: SURFACE CONDITION

E Excellent
A Acceptable
P Poor
U Unknown

CRITERION	SURFACE CONDITION MEASUREMENT METHODS				
	Stylus etc.	Speckle, etc.	Optical Power Spectrum, etc.	Strehl Ratio, etc.	Other (Specify)
SURFACE SPECIFICATION	12 E 13 A 7 P 3 U	7 E 7 A 10 P 6 U	7 E 10 A 9 P 7 U	4 E 4 A 14 P 10 U	
FLEXIBILITY	14 E 10 A 8 P 3 U	6 E 14 A 4 P 7 U	5 E 17 A 5 P 6 U	3 E 6 A 10 P 10 U	
INTERPRETABILITY	17 E 11 A 3 P 2 U	1 E 9 A 14 P 7 U	5 E 15 A 7 P 6 U	3 E 7 A 12 P 10 U	
SIMPLICITY	12 E 9 A 3 P 2 U	4 E 12 A 6 P 7 U	2 E 14 A 11 P 7 U	4 E 8 A 8 P 9 U	
ACCEPTABILITY	13 E 13 A 6 P 2 U	4 E 6 A 12 P 7 U	4 E 12 A 9 P 7 U	2 E 11 A 9 P 10 U	

No doubt many conclusions can be drawn from these data. The informal nature of the survey and the relatively small number of respondents (41) do not support a formal statistical analysis. As technology is not democratic, decision by voting is unsupportable. The results do admit some interpretation though.

First, and most obviously, the experts do not agree. Some disagreement may come from confusion on criteria, but it seems safe to say that much of the disagreement relates to subjective perceptions, or as one correspondent preferred, "taste buds".

Second, there seems to be a high level of satisfaction with existing testing methods. The number of respondents finding at least one "excellent" method for "Acceptability" was 37, or 90%.

Third, and more tentatively, surface contour measurements (Twyman-Green, Focault, etc.) seem to be more popular than surface slope measurements (shearing interferometers, Ronchi tests, etc.).

COMPARISON WITH DE VANY'S SURVEY

De Vany (1) let "opticians" test the Ronchi grating (2), Bates shearing interferometer (3), Koester wavefront reversing interferometer (4), Franco-Veret compensator interferometer (5) and a Babinet compensator interferometer of his design on a telescope in autocollimation. Their preference, apparently for convenience and versatility, was the Ronchi test.

On our survey the method giving the most combined excellent and acceptable rating for "simplicity" was also the Ronchi test (85%). On the perhaps-more-meaningful criterion of "acceptability" the combined excellent and acceptable vote went to Twyman-Green (90%) and Fizeau (83%) with Ronchi finishing fairly low (68%).

We conclude that what pleases the laboratory optician is not necessarily overall acceptability of results to the test experts but more likely simplicity and convenience of testing.

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APPENDIX B

"DEAR JOHN" LETTERS

EXCERPTS FROM "DEAR JOHN" LETTERS

1. In my work in diamond turning (Perkin-Elmer) surface finish was considered most critical and difficult to quantify using conventional techniques. Power was of less consideration in generating surface since the machine tools employed displayed remarkable accuracy. Material consideration also played a large part in diamond generated parts.

2. Herewith is your completed survey form. As you will see from the comments page, I found it very frustrating to try to complete it. I think you could easily improve it by (a) better descriptions of the methods and, more importantly, by (b) completely restructuring the criteria - for example, how can (1) an "intuitive interpretation", (2) accurate quantitative measurements, and (3) easily translatable specification be lumped under one criterion? Or for another, why should "simple", "inexpensive" and "portable" be lumped together? How is one to rank a method which is very simple, moderately priced, and weighs three tons? Anyway, good luck with the project, and I will look forward to hearing how it came out.

3. Most of the figure testing methods are limited to testing spheres if some null system is not used. Most applications and much of the value of diamond turning is in connics and aspheres (parabolas). The best test is usually one associated with the application.

4 I suggest that you consider a Babinet Compensator Interferometer as discussed in the following references:

   1. A. S. DeVany, Appl. Opt. 4 (527) 1965 and 831 same issue. (The best optical quantitative test).

   2. A. K. Saxena, Appl. Opt. 18 (2897) 1979.

   3. A. S. DeVany, Appl. Opt. 17 (3022) 1978.

5. When the errors get more complicated the intrepretability goes up quickly, e.g. differentiating between cylinder, astigmatism etc. when all are present.

6a. I hope you don't mind all of the comments. Your task is one that ASTM and OSA wish that they could do. Someone has to start somewhere. Don't expect to complete your task over night.

6b. Comment on Figure Testing: Most of these tests are acceptable under certain functions and accuracies.

6c. Comment on Surface Condition Measurements: These would not be adequate for high energy laser mirrors.

6d. I do not think that you can define one set of measurements to test optical components for all applications. A plastic lens for a condenser has different specifications and test equipment than for a laser cavity mirror.

6d. Comment on "Flexibility": I do not think you want one system to measure all of these variables. It certainly will not be simple.

6e. Comment on A Single System For All Needs: This would greatly increase the cost of a single system.

6f. Comment on Use In Various Environments: This will either increase the cost or reduce its usefulness.

6g. Comment on Simplicity: Simple systems usually have limited ranges and functions.

6h. Comment on Acceptability: Tropel and Zygo would like this. This is going to be as hard to make happen as converting to metric.

7. For general optical shop practice the use of test plates is hard to beat. If a method is to be used that is better I suggest it be the Fizeau interferometer. Zygo manufactures an excellent unit.

   For surface finish the standard scratch and dig is nearly useless. If a surface statistical property is to be considered as a spec. e.g. rms, AA, P-V, etc. these are nearly meaningless unless the autocorrelation length is also specified.

8. As I am sure you know, these sheets over simplify the problems. The answers depend upon various situations and conditions that I have been too lazy to state. Look at paper by Shapam, Sladky and Wyant in July/August 1977 issue of Optical Engineering.

9. Figure testing method is, obviously, more a function of parameters (aspheric, transmissive invisible, absolute level of accuracy, radius of curvature, etc.) than of technique. This makes rating very arbitrary and difficult. The Fouault test of an f/8 perabola is super - but impossible at f/1.0 and so forth.

10. Experience with Ronchi test has been good. Detected irregularities in generated aspherics used in photographic objectives. I have also used forward spot from HeNe laser (small .. 3mw) scanned over lens surfaces to detect scratches and digs. Qualitative results were good. Have detected (not quantitative) 20-10 surface state.

11. I feel that the specifications of optical components and systems are often so tight that "intuitive" methods do not suffice. Heterodyne interferometers such as described in Opt. Eng. 18 (5), Sept./Oct. 1979, p. 464 seem to be the only solution; yet, a skilled operator can use the instrument as input for his intuitive interpretation.

12. You should consider listing Twyman Green and Fizeau interferometers together - both represent unequal-uncommon path, double pass interferometers. Both are commonly in use. Fizeau has more value when testing large diameter convex surfaces and also facilitates the utilization of multiple beam (Fabry Perot) fringes. Twyman Green is less sensitive (contrast) to interfering beam intensity and is therefore more useful when testing varied reflectivities.

13. DOD needs something to replace MICOH 3830 for precision surfaces - very subjective.

    UDRI presently developing automatic interferogram reading equipment for straight-line and circular fringe patterns. Call me for more information - paper to Optical Engineering soon.

    Technology study should look at American Society for Testing and Materials Test Standards. ASTM Committee F1.02 working in this area. Chairman, J. Detsir, University of Daytona Research Institute. Committee wants to know what test standards are needed, will work on those if interest and people to work on them. List of present ASTU standards.

14. We are testing primarily in situ multi-element lenses for high resolution lithography (e.g. 1um resolution over 10 mm x 10 mm fields and distortion of about 0.2μm).

    Horizontal and vertical lines of special test patterns are used for testing. Uniformity of linewidth and distortion differences are measured to within ± 0.05 μm. Etched chrome images and high resolution emulsion images are measured. Images from different systems have been exposed onto the same substrate side by side for accurate comparison. We also vary the image plane and object plane in a controlled fashion to ascertain near optimum conditions.

    The individual lenses of the objectives are preselected by the manufacturer using test glasses or interferometric means.

15. It will be difficult to establish a uniform acceptance testing method. Particular cases require particular methods for optimum results.

16a. Comment on Figure Measurement: Surface point contact probing for diamond turned parts - rotational, symmetric, usually.

16b. Just as many different test techniques are required to check the variety of conventional optics - so will many methods exist for checking diamond turned optics. On-machine holographic methods using computer generated holograms is perhaps the best future direction. It is presently state-of-the-art at two companies - yet could hardly be offered as a realistic standard. At present, the very best standard exists - whatever is specified to optimize system performance. Do we need more?

17. Attached are my responses to your questionnaires. I did have some difficulty with your choice of categories. For example, by Burch interferometer I assume you mean a scatterplate interferometer which I consider a useful though somewhat limited shop or inspection tool. In my mind this is quite different from the Smartt, which in my experience has been a clever idea which is only useful or required for very specialized applications. I found myself unable to lump them into a single category for rating.

By Ronchi test there is some ambiguity as to whether you intend the Ann Arbor Optical Tester where the light source and measurement plans are coupled or the true Ronchi test where the grating is inserted near a star image. The former is a very portable, but qualitative device whereas the latter is a true shearing interferometer.

18. I would suggest this survey be restructured to evaluate the various test and specification techniques in the separate frameworks of surface and system testing, as the problems encountered are very different. For example, a star test has little value in the test of a convex optical element, but is an ideally simple test of a complete telescope.

19. The term LUPI has become an Itek "trademark" rather than an acronym.

Realistic evaluation demands knowledge of precision and packaging requirements. A purely qualitative evaluation seems to fall short of real meaning. For some applications a simple star test might suffice. For others one might require phase measuring interferometry - a category not mentioned.

Regarding "flexibility" - I do not see how any one inspection "system" could handle the variety of conditions imposed. A series of tests would be appropriate. The "system" is then an array of instruments.

20. It was hard to give unambiguous answers. It is much easier to select a test in given circumstances than to give general ratings. I will watch correlation of the answers.

21. By eliminating global measurements you forbid integrating methods such as OTF, stray light, etc. which correlate surface accuracy and surface quality with image quality which, of course, is "where its at". In many cases transfer functions are very sensitive to those qualities which are important to the shop optician, assembly technician, test technician, optical project engineer and customer.

22. It is almost impossible to specify any one test that will serve all shapes. A more realistic survey will result if optical surfaces will be categorized into: Plano, concave spheroids, convex spheroids, concave aspheres, convex asphers, cylindrical CC and CX, axicons, waxicons, etc. ....

Surface condition tests are W.R.T. small samples. Most or perhaps all of the existing surface test equipment is limited to smaller samples and much of it is limited to flat surfaces.

23. From looking at your survey and from looking at your cover letter, it seems that the former does not address at least a couple of pertinent matters. (1) Most systems can be made more or less versatile, depending upon the amount of auxiliary optics hardware which one is willing to afford. (2) Several of the systems become more or less flexible and accurate also, depending upon the amount and sophistication of data-processing hardware (and/or software) which one can afford, as well. (3) Before these things can be answered I think that the first questions to be asked, for the production testing of diamond turned optics are: How complex are the shapes to be tested and how many of a given type. At this point I can hardly imagine any one type of test being specified for diamond turned optics generally, either for surface finish or figure.

24. Using the simplicity requirement given, only the common path interferometers could be rated as excellent in simplicity. Inexpensive in our environment is far different from inexpensive in a 3-man fab. shop.

25. I have the impression that you are looking for a "universal" test for figure or wavefront and a similar "universal" test for surface condition (or roughness). There is no such thing, just as there is no "universal" diamond turning or optical polishing machine. The type of components used in optics is of too wide a variety and complexity for one type of test to work for all.

Your very ground rules for test selection rule out any of the tests listed. What interferometer is useful from visible through the infrared or what surface measuring device is global enough to determine the effect of roughness on function yet specific enough to locate and catagorize the surface defects?

In addition to the problem of universality, there is the problem of functional or acceptance type tests versus working or in-process type tests.

System acceptance tests should be completely functional such as resolution, star or MTF tests. The test should determine whether or not the system passes a functional performance specification independent of wavefront quality or beauty defects. This should be the only purpose of the acceptance test; acceptability of function. If the system passes, the vendor gets paid; if it does not pass, the system should be subjected to one or more diagnostic tests. If the problem is not relatively easily diagnosed, it may be cheaper to throw the unit out than worry about it.

In-process tests, on the other hand, permit control of the manufacturing process yet usually have nothing to do directly with function. We only infer (usually with high degree of accuracy) that if a lens has a certain power and irregularity the system it goes into should work if everything has been made and assembled properly. Yet we can, when making a large volume of systems, see the influence of in-process specifications and tests on the results of acceptance tests. It would seem to be smart business to loosen in-process specs to the point where a statistically significant impact is made on the final acceptance testing.

Philosophy aside, the type of test device which appears to be most universal is the large aperture type Twyman-Green or Fizeau type interferometer such as the Zygo or Tropel. The large aperture coupled with a fast diverging lens makes it possible to test convex surfaces (the real plus for test plates) as well as concave surfaces. If these same instruments were modified to remove the reference wave front and block the zero order beam from the test object, the instrument could be used for either qualitative or (with further modification) quantitative surface condition measurement. Of course this would make an already expensive and somewhat complex instrument that much more complex and expensive. But it would be reasonably universal.

25. Contd.

On the side of simplicity, I think we should look harder at some of the classical slope measuring tests such as the Ronchi, Hartmann and Foncault tests. We have shown that results from these tests may be quantified using existing interferometric fringe reduction software if a numerical answer is needed while test patterns are easily compared to some standard pattern for use in an acceptance test mode. Certainly nothing could be easier to set up and get a "fringe" pattern than a Ronchi test.

Finally, let me comment on diamond turned optics specifically. One really does not care if an optic is diamond turned or not as long as the system into which it is introduced still performs acceptably. Therefore, various quality levels of individual components should be substituted in the system and its performance measured. An empirically determined correlation between ultimate function and surface roughness may then be used to set in-process specifications. I do not think the theory of the effect of surface roughness on optical performance has been worked out well enough to do this theoretically.

From our own work on diamond turned surfaces we have found that scattering (in particular low angle scattering) is the most detrimental attribute of diamond turning. Also the scattering increases as the third power of surface roughness so that mechanical profilometry or microinterferometry are not very sensitive indicators of scattering. Direct measurement of scattering seems to be the most direct and reliable measure. However, scattering is easily measured only on plano surfaces.

As I see it, there are two choices, both empirical but easily quantified. First, one could make a scatterometer for curved surfaces which would simply be calibrated for each different curve in an empirically determined manner. The device would first be adjusted (by moving the detector) to find the specular reflection from the surface. The output of a second detector mounted such that it is always some small (perhaps 3°) angle off specular would then be compared with the specular reading. The acceptable ratio for these readings would have to be determined empirically. It would be, however, an easily performed test and the scatterometer is simple and inexpensively made.

The second choice would be to set up a Twyman-Green interferometer as described above where the zero order light reflected off the surface under test is intercepted by a detector. The scattered light is imaged on a second detector. Again, the ratio of the two signals would be the criteria for acceptance and this level would have to be determined empirically. It could weel be that with some experience with diamond turned optics, a rule of thumb could be devised around which a specification on scattering could be written. It certainly seems a fruitful area for a little research and could seel be applicable to conventionally produced optics as well.

I hope these comments are useful. Please keep me informed on how your study goes.

26. Your questionnaire has me wanting to explain and qualify each answer. The best testing method for a given part depends on the quality of the surface, the shape (flat, severe aspheric, etc.), the application of the part, its size and the number of parts to be tested. I would suggest you consider using Jim Wyant at the University of Arizona as a consultant to help set up the goals of your study. I would be glad to discuss this study with either you and/or Jim.

27. Meaningful descriptions of testing methods and equipment available by experienced test personnel would be quite valuable to the whole optics industry. (In terms of hands-on testing).

28. It is important to keep in mind the following aspects:

    Very frequently it is better to use at least two methods of testing.

    Also is recommendable to use one test, under different situations (e.g. two or three focus positions).

    The use of a specific test depends on the type of surface under test, and the specific aberrations or defect to be analyzed.

    It will be interesting to know for a special surface or system, which test will be recommended for several people (like a homework).

    Bibliography: Optical Shop Testing, Ed. Daniel Malacura, John Wiley (1978)

    Notes on Optical Shop Testing and Production, OSA, in different years.

29. Any and all of the methods listed can and should be used under proper circumstances. These questions are inadequate to support specific answers. The type, quality, material, can impact measurement technique usefulness. Functional testing by traditional optics methods is necessary to provide the final component evaluation. However, for precision machined surfaces, a geometric evaluation for surface contour and locations as well as surface roughness is also needed. Maximum flexibility and quality can be obtained from precision machining by taking advantage of the inherent repeatability of a well managed machine. The ability to measure mechanical error and make corrections is vital.

30. Your letter of 28 November was most irresistible. Unfortunately the interpretation of your questionnaire is a bit difficult with respect to what we do to quantify the characteristics of ring laser gyro optics.

First of all, we do not do diamond turning and may thus have no place in your survey. Secondly, we are designing and building special instrumentation in the Ring Laser Gyro Laboratory at the Avionics Laboratory at Wright-Patterson AFB to measure a light scatter profile for each reflector in a gyro. The technique may not be usable for bare substrates, since it was primarily designed for MLD optics. We have not tried to evaluate a substrate so all we can say is that we have no data.

Our procedure would, or could, be applicable to front surface reflectors such as the diamond turned copper reflectors being used in IR work. Again, we have no data, but the idea is feasible.

Our substrates are specified by surface roughness, primarily. We try to stay under 7 angstroms RMS surface roughness. Our flats are as near to .01 λ as we can get in the center 2 mm. The coatings themselves are quite special and are designed to yield a minimum of scatter. Our RLG optics have been tested by one gyro manufacturer and are reported to be the lowest scatter optics (by an order of magnitude) available anywhere. Needless to say, they are all special order.

Since I am not certain how we fit your questionnaire, I will take my best shot and you can use the data as you see fit.

31. Most of the test methods in Part One suffer in their inability to be used well in the rolling atmosphere if precision is required and the distances are more than a few cm. For example, testing a long focus lens or fairly flat sphere at its c. of c. in air is often impractical if not impossible.

APPENDIX C

SAMPLE PAGES FROM BIBLIOGRAPHY

1 NEWTON, FIZEAU, AND HAIDINGER INTERFEROMETERS

1.1 NEWTON INTERFEROMETER

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Optik, 5, 354 (1949)
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Appl. Opt., 9,. 837 (1970)
The shape of any aspherical surface with rotational symmetry can be very easily found with great accuracy using Newton fringes formed against a spherical test plate. To make it possible, a special mathematical procedure is devised for use with a special measuring system here described.

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"FRINGES, THEIR SENSITIVITY ACCORDING TO TEST CONFIGURATION"
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1.1 Newton Interferometer
- 1.1.1 Source Size Considerations
- 1.1.2 Some Suitable light Sources
- 1.1.3 Materials for the Optical Flats
- 1.1.4 Simple Procedure for Estimating Peak Error
- 1.1.5 Other Applications of Newton's Interferometer

1.2 Fizeau Interferometer
- 1.2.1 The Basic Fizeau Interferometer
- 1.2.2 Liquid Reference Flats
- 1.2.3 Testing Nearly Parallel Plates
- 1.2.4 Fizeau Interferometer for Curved Surfaces
- 1.2.5 Monochromaticity Requirements for the Source
- 1.2.6 Fizeau Interferometer with Laser Source
- 1.2.7 Multiple-Beam Fizeau Setup
- 1.2.8 Testing the Inhomogenity of Large Glass of Fuzed Quartz Samples
- 1.2.9 Testing Cube Corner and Right Angle Prisms
- 1.2.10 Testing Concave or Convex Surfaces
- 1.2.11 Quality of Colimation Lens Required

1.3 Haidinger Interferometer
- 1.3.1 Applications of Haidinger Fringes
- 1.3.2 Using of Laser Source for Haidinger Interferometer

1.4 Absolute Testing of Flats

AD-A101 036 AERODYNE RESEARCH INC BEDFORD MA F/G 20/6
MMAT: TESTING OF ELECTRO-OPTIC COMPONENTS.(U)
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UNCLASSIFIED ARI-RR-215 DRSMI/RH-CR-81-8 NL

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Appl. Opt., 10, 929 (1971)
Methods proposed by the authors to establishing a flatness standard without using a liquid mirror are proved in practice and extended. The extension is performed by a development of methods for the determination and compensation of random and systematic measuring errors by means of condition equations which must be satisfied by the measured sums of deviations from absolute planeness. Linear errors of these sums of deviations which can lead to ambiguities and errors of planeness deviations can be discovered and completely eliminated. Also nonlinear errors, for example, as a result of temperature differences or of mechanical stress, can be recognized without repeating the interference photography procedure. The deviations from absolute planess of three fused silica plates were determined along seven diameters (angular distance 2 pi/14) with an accuracy of lamda/500 (mean square error). This was perfomed by evaluating two sets of four different interference photographs, each with contour plane distances of lamda/50 (from fringe to fringe).

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Descriptors: OPTICAL TESTING; OPTICAL GLASS; LENSES; SURFACE TOPOGRAPHY MEASUREMENT; LIGHT INTERFERENCE;
Identifiers: FLAT; INTERFERENCE FRINGES; NEWTON'S RINGS; ERRORS; TEST GLASS RADING; POLLISHED OPTICAL SURFACE CONTOURS

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Opt. Eng., 14, 520 (1975)
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Opt. and Laser Technol. (GB), 9, 158 (1977)

Describes a modified Fizeau interferoscope which has been developed for testing aircraft camera windows measuring up to 50 cm in diameter. Relatively cheap components are used for the large collimating lens and reference flats, and a small holographic optical element corrects for the residual errors of form (2 Refs)

Descriptors: OPTICAL TESTING; LIGHT INTERFEROMETRY; OPTICAL ELEMENTS; CAMERAS

Identifiers: LARGE INTERFEROMETER; AIRCRAFT CAMERA WINDOWS; MODIFIED FIZEAU INTERFEROSCOPE; LARGE COLLIMATING LENS; REFERENCE FLATS; SMALL HOLOGRAPHIC OPTICAL ELEMENT; AERIAL PHOTOGRAPHY

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Optical Shop Notebook, Section IX, 69 (1975)

INTRODUCTION

Interferometric fringe data reduction has been done subjectively for years. The evaluation was done by eye so that the quality of optical components was established qualitatively. Large companies have utilized complex computers to get quantitative data, but these methods have been beyond the reach of the majority of optical shops. We show here that it is now possible to do this analysis with a minimum of optical equipment and a relatively inexpensive desk-top calculator.

The type of fringes we are concerned with are formed by an interferometer of the reference wavefront type (as opposed to the shearing interferometer), and they can be obtained from a wide variety of test configurations. These include the methods known as Fizeau, Twyman-Green, laser unequal path, scatterplate, and test plate, among others. In all of these configurations, a wavefront is generated which is assumed to be perfect. This reference beam and the beam which samples the test element are combined and interfere with one another to produce light and dark bands. A tilt is often introduced between the two beams in order to get fringes which are more or less straight. The title is mainly a convenience. With appropriate techniques, the patterns obtained without a tilt (bull's eye fringes) can also be analyzed, though it is somewhat more complex and time consuming. A photograph is generally taken of the fringe pattern in order to get a permanent record and to be able to study the fringes without the vibrations often associated with viewing them in real time.

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Feingeraetetechnik (Germany), 26, 488 (1977)
Languages: GERMAN
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Descriptors: LENSES; OPTICAL TESTING; LIGHT INTERFEROMETRY; CURVATURE MEASUREMENT
Identifiers: SPHERICITY; LENSES; NONCONTACT TESTING; INTERFEROMETER

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Descriptors: LIGHT INTERFEROMETRY; OPTICAL TESTING; LENSES; ABERRATIONS
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Descriptors: LIGHT INTERFEROMETERS; OPTICAL TESTING; LENSES; LIGHT DIFFUSION
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